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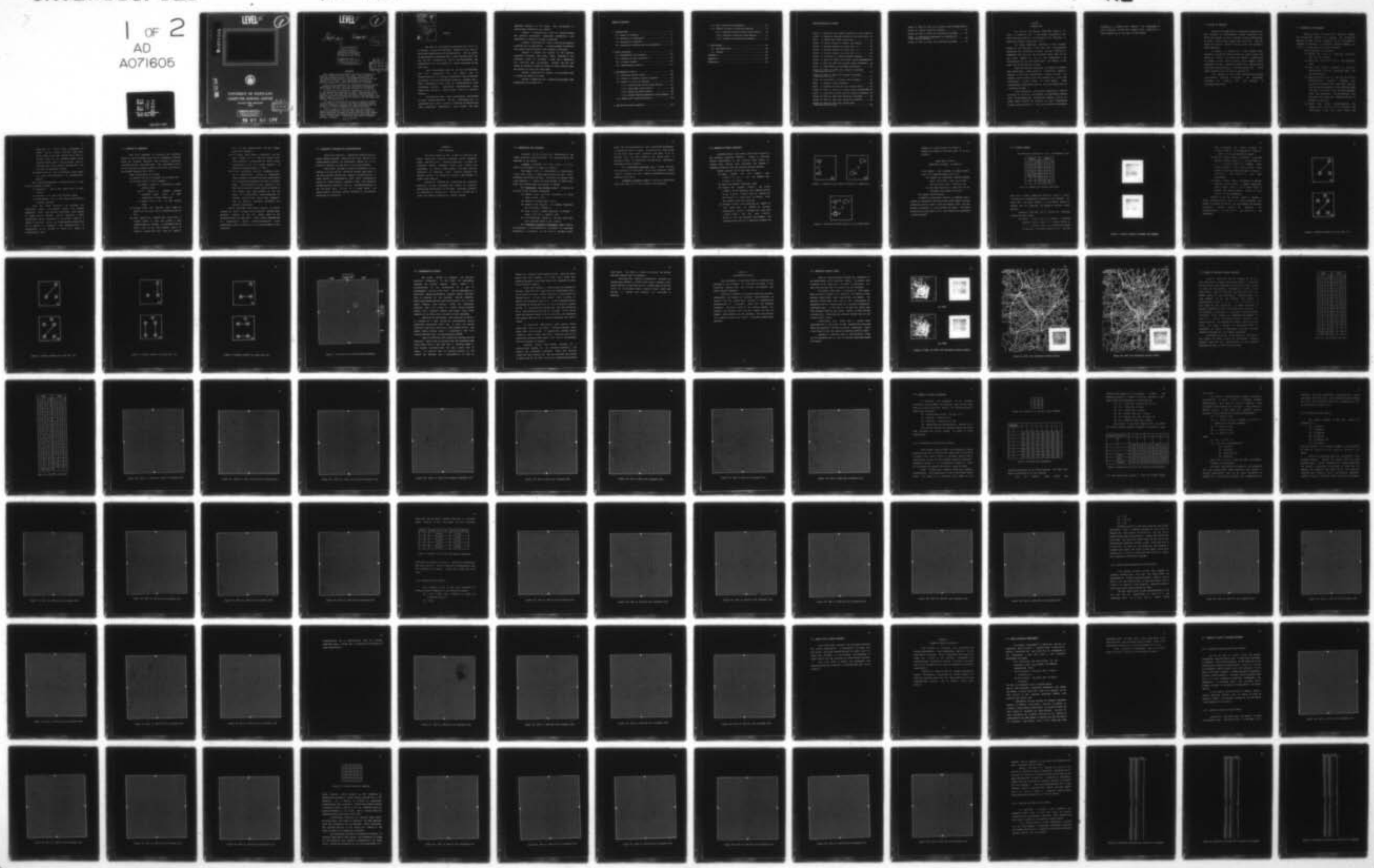

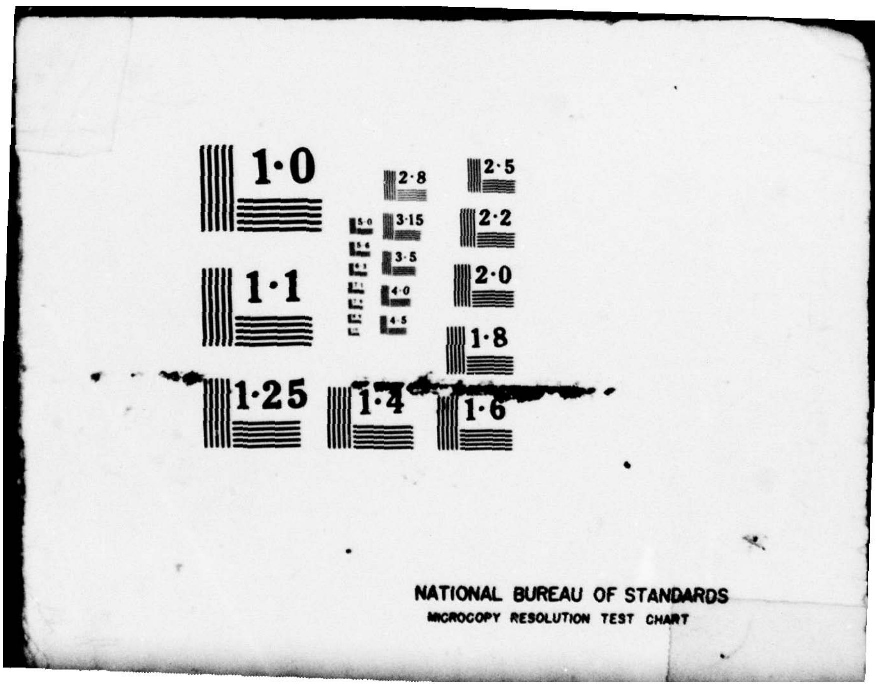
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(6) SKETCH MATCHING

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Abstract

This report investigates the problem of matching two different sketches of the same scene. The process of matching enables pairing of corresponding parts of the two sketches thus allowing registration of one sketch with respect to the other. Once registered, detection of matching subpatterns and/or discrepancies is possible.

Sketches are represented as structured arrays of points (Cartesian coordinates and other associated information which embody the most important features of the sketch).

Two sketches are matched by comparing all point pairs of one sketch with those of the other. The decision as to whether or not one point pair (fuzzily) matches another is based on how well the length and slope of the imaginary line segment between the first pair coincides with the length and slope of the second pair.

The power of the matching process is tested by adding varying amounts of noise--in the form of Brownian motion, rotation, rescaling, random point additions/deletions--to determine how fast successful performance degrades.

Several means of reducing/combatting the effects of noise are considered. The two most important ideas are adding additional information about each point and attempting to determine the rotation/scaling of one sketch with respect to the other. Suggestions for further research are also included.

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PREFACE

The goal of the research underlying this report is to develop a basis for additional research in the area of map-guided segmentation and interpretation. That is, given an appropriately represented map of some arbitrary area, one can use that information to aid in the segmentation and interpretation of, for example, an aerial photograph of the same area.

After corresponding parts of the map and photograph have been determined, the two images may be "differenced"; that is, matching subpatterns may be factored out, leaving only the differences (objects, changes, etc.). These discrepancies could then be "interpreted" by some intelligent process. Appropriate interpretation could reveal such things as tumors, dental caries, or military targets.

Specifically, this report investigates the problem of point pattern matching. The map, photograph, etc. is represented as a list of points (Cartesian coordinates and other associated information) which embody the most

important features of the image. This information is collectively referred to as a sketch.

Chapter 1 introduces the topic of sketch matching and provides appropriate background information. Also presented is a review of related literature.

Chapter 2 describes the basic, brute force matching algorithm and its motivation. A simple example illustrates the various steps involved in the process of matching.

Chapter 3 relates the results of the matching algorithm in several test cases. First, sketches of two different (types of) pictures, a tank and a Washington D.C. area road map, are matched. Second, the road map sketch is matched to copies of itself to which varying types and amounts of noise have been added.

Chapter 4 describes the results of two methods used to reduce the effects of noise.

Chapter 5 summarizes the research and presents some suggestions for further work.

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List of Figures and Tables

CHAPTER 1
INTRODUCTION

The goal of the research described herein is to build a foundation for a map-guided segmentation and interpretation system to be developed by the University of Maryland's Computer Vision Lab (CVL).

The basic, underlying philosophy of the proposed system is the following. If one has a map of appropriate resolution and information content and some method(s) of segmenting that map into its constituent parts, then one can use those results to aid in the segmentation and interpretation of an aerial photograph, for example, of the same area as described by the map.

While the map and photograph are certain to contain many differences, there should be a significant number of features (call them subpatterns) common to both. For example, rivers, lakes, major road systems, etc. (call them subpatterns) should appear on both images. These corresponding subpatterns could be put into registration by a matching process.

Once registered, the matching subpatterns could be factored out of one or both images, as appropriate, leaving only the discrepancies, differences, changes, and so on. These would finally be examined by some "intelligent" process having access to a data base containing information

necessary to interpret such remnants. The development of such a matching system from a simple, basic algorithm to a more powerful one is the topic of this thesis.

1.1. Domain of research

Much work has been done on image region matching for such purposes as stereomapping, change detection, etc. While this approach is very important in many applications, it cannot tolerate much geometrical distortion. For that reason the author's research has dealt with the problem of sketch matching.

A sketch, in general, is a line drawing which represents significant region boundaries, lines, curves, and points in a scene. For simplicity, however, a sketch will be defined as that set of points (point pattern) which represents the most important features of a sketch such as line/curve intersection(s), curvature maxima, etc. A more formal definition can be found in Section 2.1.

The remainder of this chapter describes the relevant point-pattern matching literature. All algorithms, including the author's, deal with patterns in two-dimensional space.

1.2. Matching by ordonnances

Simon, Checroun, and Roche [S1] discuss a process for recognizing patterns of N points. The recognition process is based on the comparison of the "ordonnances" obtained by ordering the Euclidean distances between the N (N-1) / 2 point pairs of the given pattern.

Their algorithm is as follows:

(1) Compute the N (N-1) / 2 point-pair distances, d (i), for each pattern.

(2) Index sort each list of d(i)'s into descending order.

(3) Using the indices generated in step (2), respectively, order the point-pair label list for each pattern.

(4) Compute from the lists of step (3) new lists in "parenthesized" notation. Assuming each distance was computed with some error, epsilon, then perhaps some members of the distance lists (and hence label lists) may have been permuted. Given this assumption, the parenthesized list indicates which label list members' order may be permuted in step (5).

(5) Select some label, (point) A (point) B, for example, from one list; say it occurs as the first member of the list. Next, locate (the

positions of) the N-2 other occurrences of point A (or B). Select, from the other list, those labels at the same possitions as point A. If some point, A', for example, occurs in all selected labels, then A may be paired with A'. Determine any other possible pairings for A in the event of permutable labels.

(6) Repeat step (5) for any remaining points until all have been successfully or unsuccessfully paired.

The Simon/Checkroun/Roche algorithm results in one of three possible outcomes:

(1) impossible - one or more points have not been paired,

(2) possible - all points are uniquely paired,

(3) undetermined - one or more points have multiple possible pairings.

While the ideas underlying the matching are intuitively sound, the process itself has several weaknesses. First, only patterns containing equal numbers of points may be matched. Second, declaring a match "impossible" may be incorrect as one pattern could be a subset of the other. Third, no disambiguating process such as or similar to relaxation (see Rosenfeld [R1]) is incorporated in an attempt to reduce the number of "undetermined" cases.

1.3. Matching by templates

Zahn [Z1] describes an algorithm for detecting whether or not one planar point set is a fragment of another which has possibly undergone some arbitrary similarity transform and has had noise added. The algorithm is built on the similarity invariant aspect of the local structure of the minimal spanning tree (MST).

Zahn's algorithm is as follows:

(1) Compute the MST for fragment (f) and base (b).

(2) For each node of f and b compute:

(a) degree - number of connections to other nodes via MST

(b) if degree >= 2, compute minimum subtended angle (MSA) by edge connections to other nodes, and

(c) length ratio (LR) of the minimum angle.

(3) Arrange nodes into separate lists based on degree and sort each list on increasing value of MSA.

(4) Scan through the fragment node lists until a "simple match" on some node yields a good template match or fragment is exhausted with no match. That is, for each fragment node f of degree D, search base node lists, in order D,

D+1, D-1, for matching MSA's and LR's modulo some error tolerance.

(5) If a simple match check is successful for some pair of nodes (f, b), test for a "local-fit"; check geometric consistencies of MSA's (angle registration) and LR's (scale factors) of respective neighborhoods of f and b.

(6) If just one MSA/LR match is successful, then try a "global-fit". Solving an appropriate linear system of equations provides coefficients for a similarity transform from base to fragment space. The transform is then applied to all base points and each fragment point is mapped to its nearest base point neighbor in the new space. If a sufficiently large proportion of frequent points match, modulo some tolerance, then the match is considered successful and searching terminates.

Zahn's algorithm works fairly well;it is rather tolerant of scale, rotation, and translation between point patterns. However, it does not handle noise of the Brownian-motion type very well. Also, certain combinations of insignficant random additions/deletions could sufficiently alter the MST so as to be unrecognizable to his algorithm.

1.4. Similarity relations and autocorrelation

Seidl [S1] discusses a similarity relation based on mutual nearest neighbor conditions and a new (M-1)th order autocorrelation method for determining whether an M point pattern is similar, in some way, to an N point pattern.

Since Seidl presents no explicit algorithm per se, suffice it to say that he determines whether some subset of one point pattern matches some subset of another pattern if there exists a transformation under which corresponding points are mutual nearest neighbors. Seidl also considers autocorrelation similarity, that is, determining whether or not the chord sets - N * (N - 1) / 2 point pairs - are mutual nearest neighbors similar according to his extended definition of similarity.

CHAPTER 2

BASIC ALGORITHM

The major concern of this chapter is describing the basic, brute force matching algorithm and all necessary terms, notations, etc. Although simplistic, in cases of reasonably similar sketches, fairly good results are obtainable. As will be seen, however, not much noise or distortion is tolerated. Later chapters describe the effects of noise in detail and present some methods to reduce those effects.

Section 2.1 defines the terminology and notations which will be used throughout this thesis. An informal, step-by-step description of the basic algorithm (PTM/BA) is presented in Section 2.2. Section 2.3 carries out a brief, but complete matching on a simple example.

2.1. Terminology and notations

Contained in this section are definitions of the terms, notations, data structures, etc. used throughout the remainder of the thesis.

A sketch is defined as a set, { P(i) | i = 1,N }, where N is the number of points in a sketch.

Each point , P(i), is represented by a three-tuple, [x(i), y(i), jt(i)], where x(i) and y(i) are the X and Y Cartesian coordinates and jt(i) indicates the junction type (see Appendix A) similar to those defined by Waltz [W1]. NOTE: all junction types are ignored in PTM/BA.

The "Interpoint Line Segment (ILS)" structure is an array of the following components:

(1) address (into point set structure) of first point of pair (PT1),

(2) address of second point (PT2),

(3) length of the imaginary line segment connecting the two points (LENGTH),

(4) slope of that segment expressed in radians - range [+PI, -PI] (THETA), and

(5) flag indicating whether or not the point pair has a possible match or not (FLAG).

The "Cartesian Coordinate Difference (CCD)" matrix is essentially a two-dimentional histogram. On algorithm termination it contains, in the case of matching point

pairs, the positive/negative X and Y coordinate differences (translation factors) which, if added to the first point of the first pair, would translate that point so as to coincide with the first point of the second pair. A singular cluster of significant concentrations indicates a successful sketch matching.

The "Rotational Histogram (RH)" vector contains the frequencies of occurrence of relative rotations (THETA - THETA') between the line segments determined by possibly matching point pairs.

"Mismatch tolerance (TOLR)" limits how imprecisely point pairs may fail to match before being rejected.

2.2. Overview of basic algorithm

Described below is the basic, brute force version of the matching algorithm (PTM/BA). Chapter 4 describes various enhancements to this version which reduce the running time, improve noise tolerance, and attempt to determine relative scale and rotation between sketches.

PTM/BA consists of the following steps:

(1) Input values for the SKETCH1 set, { P1(i) | i = 1,N } , and the SKETCH2 set, { P2(j) | j = 1,M }.

(2) Input the mismatch tolerance, TOLR.

(3) Compute the lengths (LENGTH) and slopes (THETA) of the imaginary line segments defined by the N (N-1) / 2 point pairs of SKETCH1 and the M (M-1) / 2 point pairs of SKETCH2. Store the results in the ILS structure.

(4) Attempt to match each point pair of SKETCH1 to each point pair of SKETCH2 as follows. Referring to Figure 1, consider the point pair [P1(1), P1(2)] and the pair [P2(1'), P2(2')]. Let the imaginary line segment A be considered one side of an imaginary triangle and

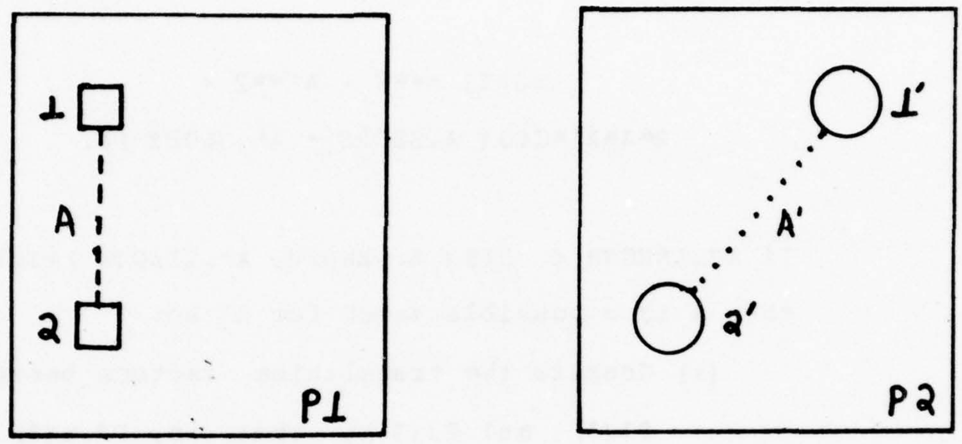


Figure 1. Imaginary line segment defined by a point pair.

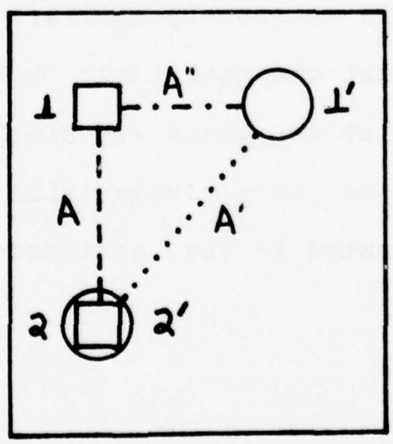


Figure 2. Imaginary triangle defined by two point pairs.

segment A' a second side as in Figure 2.

Compute the length of the third side, A", by the formula:

```
SQRT( A**2 + A'**2 +
2*A*A'*COS( A.SLOPE - A'.SLOPE )).
```

If A".LENGTH < MIN(A.LENGTH, A'.LENGTH)*TOLR, then A is a possible match for A' so:

(a) Compute the translation factors between P1(1) and P2(1'), that is, P1.x(1) - P2.x(1') and P1.y(2) - P2.y(1'), and

(b) Use these factors to index into CCD and increment that element by one(1).

(5) Display the CCD matrix.

If SKETCH1 is reasonably similar to SKETCH2, then a cluster of significant concentrations should appear at those translation factors which would map similar parts onto one another; otherwise, no such cluster will exist. The above algorithm is illustrated in the next section by considering a simple example.

2.3. A simple example

The Cartesian coordinates of the two sketches to be

SKETCH1			SKETCH2		
X	Y	JT	X	Y	JT
15	15	0	8	12	0
10	10	0	5	10	0
15	10	0	10	10	0
-99	-99	0	5	5	0
			10	5	0
			-99	-99	0

Table 1. SKETCH1 and SKETCH2 point-data.

used in the simple example are listed in Table 1. Figure 3 displays the topographical structure of the sketches. The reader will note that SKETCH1 is a translated version of SKETCH2 with the uppermost and uppermost-leftmost points deleted.

Beginning with step (3) of PTM/BA, the following iterations would occur:

(1) First, [P1(1), P1(2)] of SKETCH1 is matched against [P2(1'), P2(2')], [P2(1'), P2(3')], . . . , [P2(4'), P2(5')] of SKETCH2 as defined in step (4) of PTM/BA(Section 2.2). The only

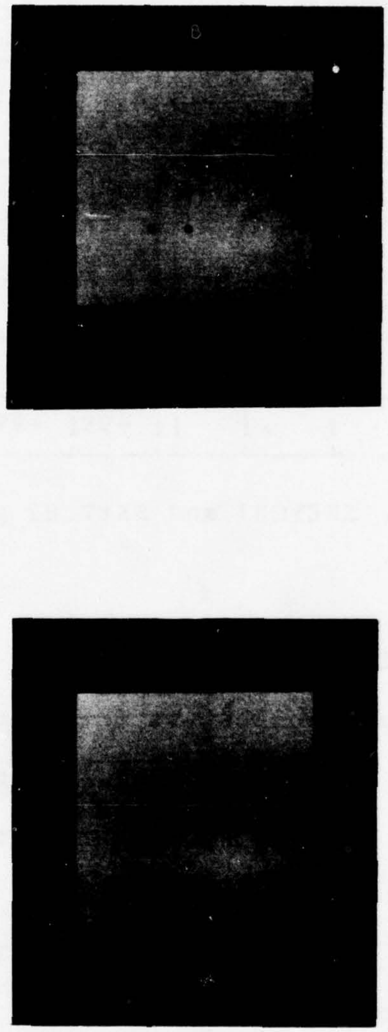


Figure 3. Graphic display of SKETCH1 and SKETCH2.

pair satisfying the match criteria is [P2(3'), P2(4')] as illustrated in Figure 4.

CCD(5, 5) is incremented by one(1).

(2) Second, [P1(1), P1(3)] of SKETCH1 is matched against [P2(1'), P2(2')], [P2(1'), P2(3')], . . . , [P2(4'), P2(5')] of SKETCH2. Pairs [P2(2'), P2(4')] and [P2(3'), P2(5')] both satisfy the match criteria as shown in Figure 5. CCD(10, 5) and CCD(5, 5) are both incremented.

(3) Lastly, [P1(2), P1(3)] of SKETCH1 is matched against [P2(1'), P2(2')]. Figure 6 shows that pairs [P2(2'), P2(3')] and [P2(4'), P2(5')] satisfy the match criteria. CCD(5, 0) and CCD(5, 5) are incremented.

Display of the CCD matrix, Figure 7, reveals a "high" concentration at CCD(5, 5) which indicates that SKETCH1 is similar to SKETCH2 and also defines the relative translation factors between the sketches. The "concentrations" at CCD(10, 5) and CCD(5, 0) are extraneous.

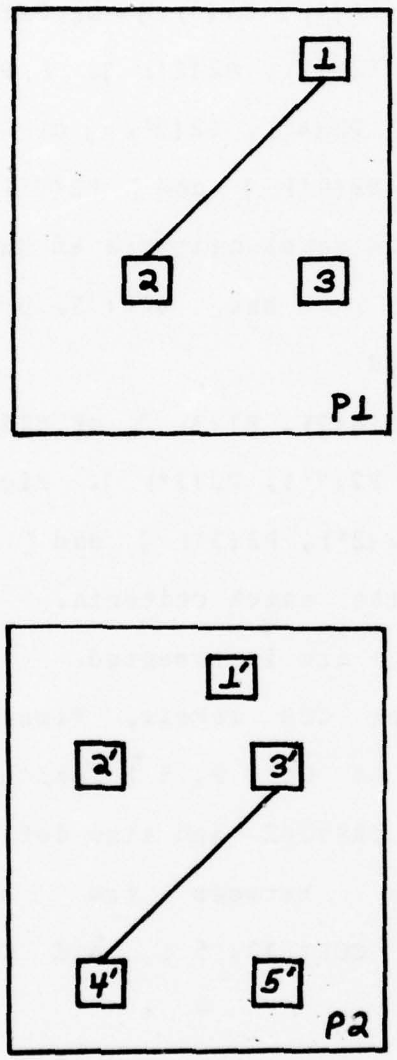


Figure 4. Possible matches for point pair 1-2.

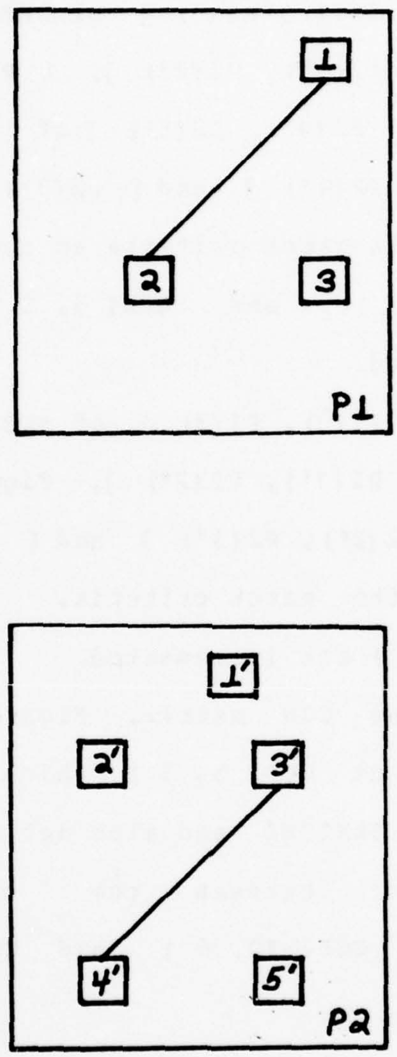


Figure 4. Possible matches for point pair 1-2.

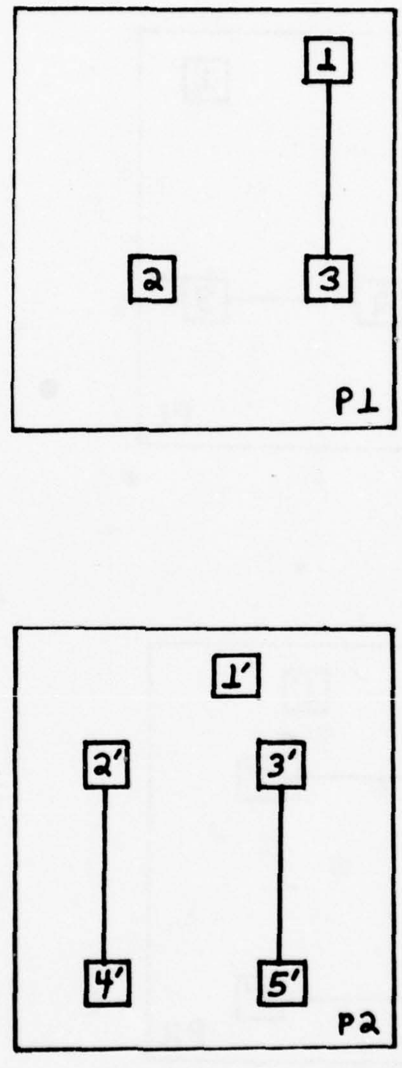


Figure 5. Possible matches for point pair 1-3.

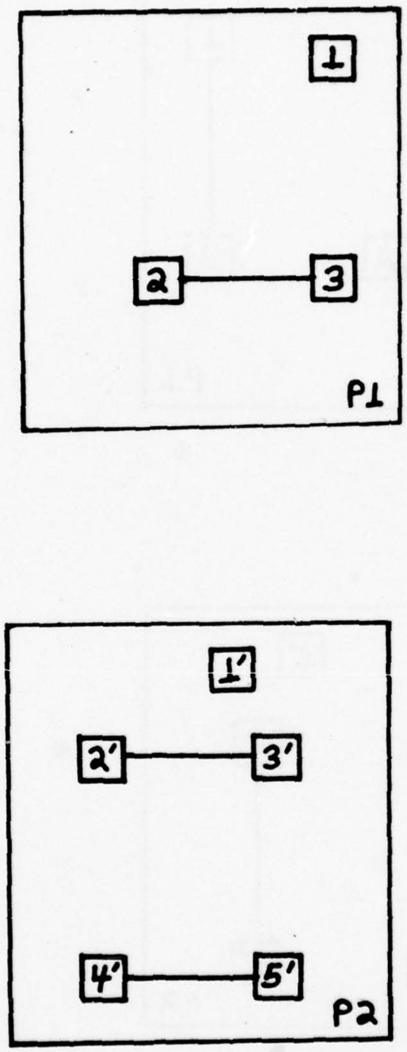


Figure 6. Possible matches for point pair 2-3.

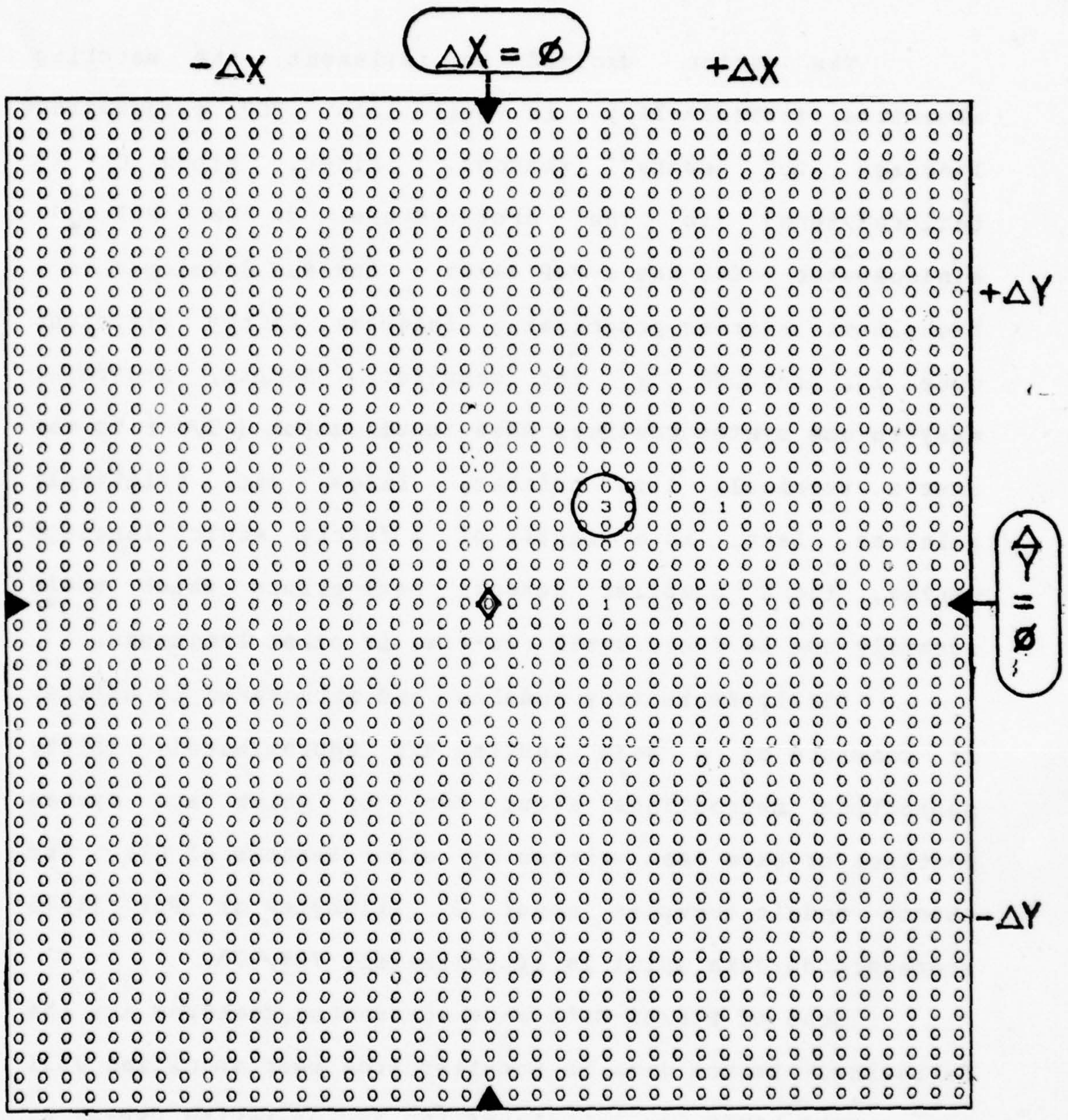


Figure 7. CCD matrix for SKETCH1/SKETCH2 matching.

2.4. Implementation details

The author decided to implement the matching algorithm (PTM/BA-EA) in Bell Labs' "C" programming language for several reasons. First, since C is tailored/tuned to the architecture of a PDP 11 minicomputer - CVL has a PDP 11/45 - and was developed as a high-level systems programming language, fairly efficient code is produced by the compiler. Second, numerous, easy-to-use system routines make input/output (I/O) to the user's terminal, line printer, files, etc. relatively painless. Last, as a result of a fairly strict language syntax, the C compiler detects many errors which would normally not be found until run-time in other languages.

PTM/EA-EA is very modular and structured in nature. It consists of a main routine and approximately thirty supporting subroutines abcut ten of which are system routines or have been written by other members of CVL. The object module occupies about 22 kilobytes of PDP 11/45 storage;code/data split is apprcximately 70%/30%.

Some of PTM/BA-EA's more noteworthy features are the following. Sketch data is inputted from user specified UNIX files(NOTE: UNIX is Bell Labs' PDP 11 operating system). This feature cbvicusly saves the user a great deal of typing. To give the user an intuitive feeling of how similar two sketches are, a representation of each is

"drawn" on a Grinnell color display system. After all point pairs have been matched, all point pairs which have potential matches in the other sketch are connected by lines on the Grinnell display.

If the user desires, a debug display is produced as follows. When the I'th point pair(the "stationary" pair) of one sketch is being matched against all point pairs(the "moving" pairs) of the other sketch a line is drawn to connect the stationary pair(SP). As SP is matched against one particular moving pair(MP), a line is drawn to connect the MP. If SP potentially matched MP, the line connecting MP is left;otherwise, the line is "erased". If SP had at least one potential match to one of the MP's, its connecting line remains when new SP is selected;otherwise, the line is erased.

At some point some process would have to decide which point pairs of one sketch "actually" matched which point pairs of the other. To simply this process, PTM/EA creates a (UNIX) output file which contains a list of all potentially matching point pairs. The list is in printable form for purposes of display.

Hardcopy output from PTM/EA consists of a binary-valued display of the sketches(optional), CCD matrix, and rotational histogram. After this hardcopy output has been printed, the user may terminate the program at which time he can print the list of potentially matching

point pairs. The other is choice is continue the program and match another pair of sketches.

Recalling that PTM/EA is Order(N**4), matching two twenty-point sketches (160,000 point pairs) requires about twenty seconds of real-time with an average load on the PDP 11/45. If the Grinnell debug display is done, about five minutes - a fifteen fold increase - of real-time is required.

CHAPTER 3

EXPERIMENTAL RESULTS

The performance of algorithm PTM/BA is presented and analyzed in this chapter. To illustrate the power of the algorithm, expected test case results are compared with those actually obtained.

Section 3.1 defines how feature points are selected, represented, and stored by decribing those functions in terms of two test images while Section 3.2 considers the determination of a suitable value for the mismatch tolerance. The main result of the thesis, Section 3.3, presents and analyzes the test case result for the two images. Noise effects are also examined. The last Section, 3.4, briefly describes the results of matching random point patterns.

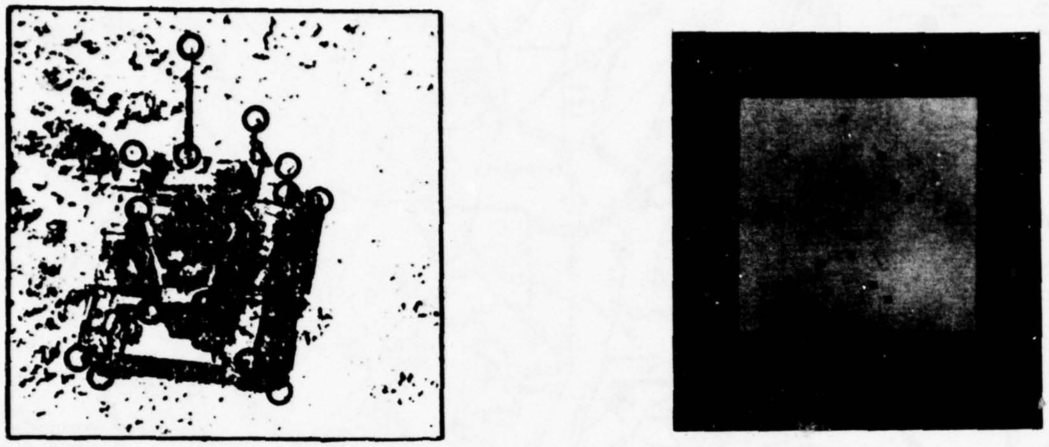
3.1. Selecting feature points

Since no map/photograph database was available, it was approximated in the following manner. Two images, one, a picture of an army tank, the other a Washington, D.C. area road map, were used to generate the test sketches.

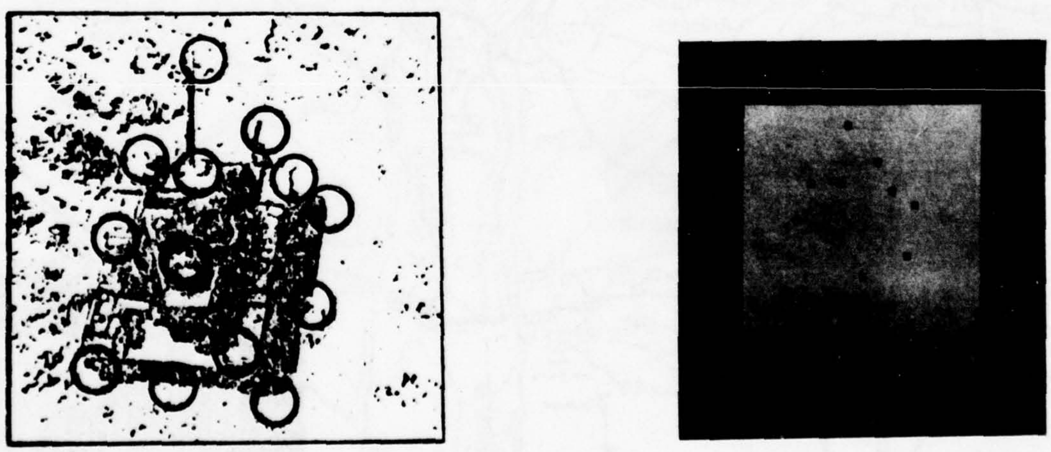
Two people were given a photocopy of both images. Each was told to select (by circling) the twenty or fewer feature points which best characterized the images. The selected points were then given X and Y coordinates by assigning each to a unique block of an overlaid transparent, coordinate grid. In the case of the map, the points were also assigned junction type labels similar to those defined by Waltz [W1]. Each point set was then entered into its own (PDP/11 UNIX) file.

Intuitively, this should give a fairly close approximation to the output of some segmentation algorithm which had processed the map and aerial photograph. Figure 8 and Figure 9 show the images and selected feature points.

Appendix B contains pictures and data-point files for all sketches used to test and analyze algorithms PTM/BA and PTM/EA.



(a) TANK1



(b) TANK2

Figure 8. TANK1 and TANK2 with designated feature points.

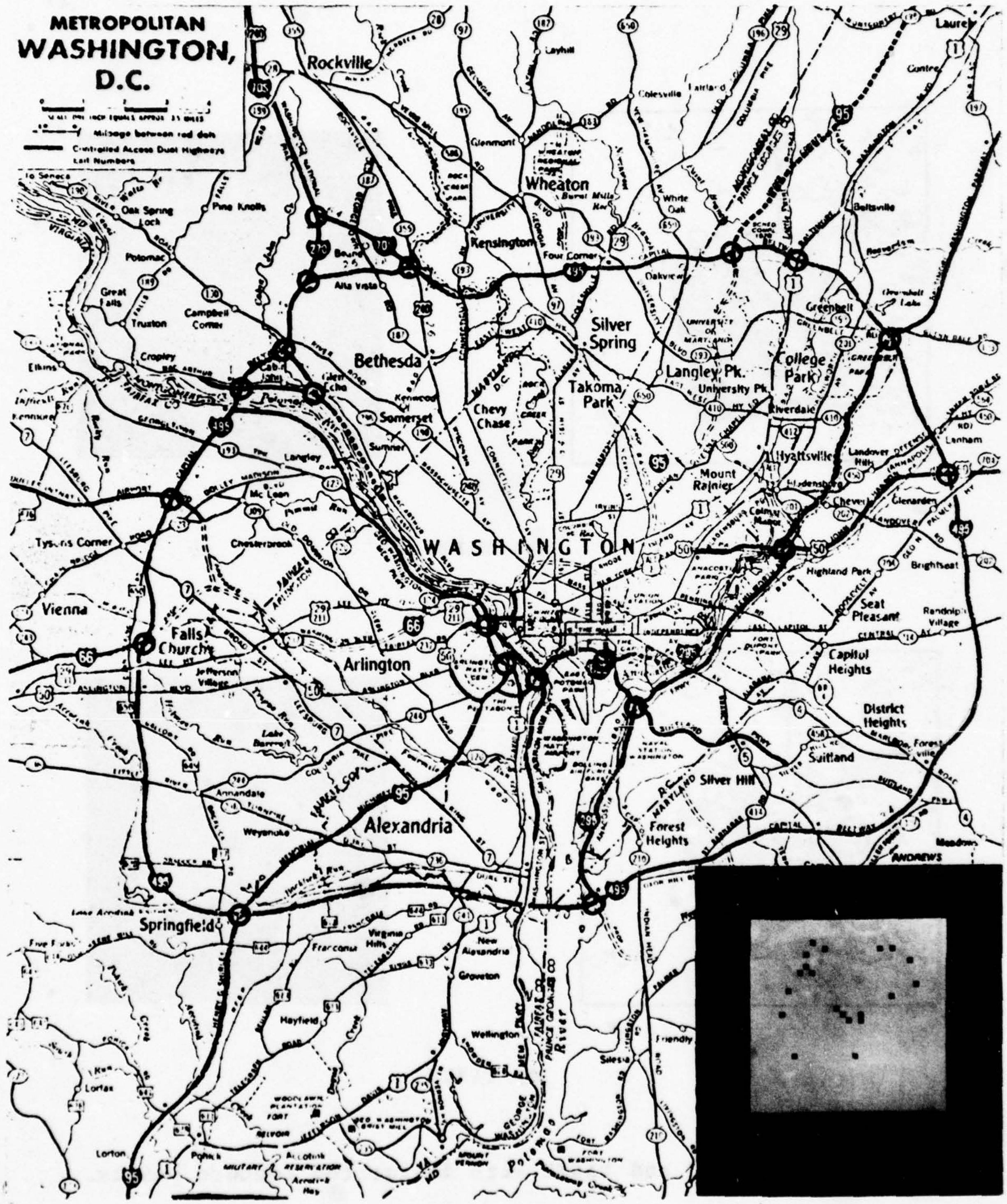


Figure 9a. MAP1 with designated feature points.

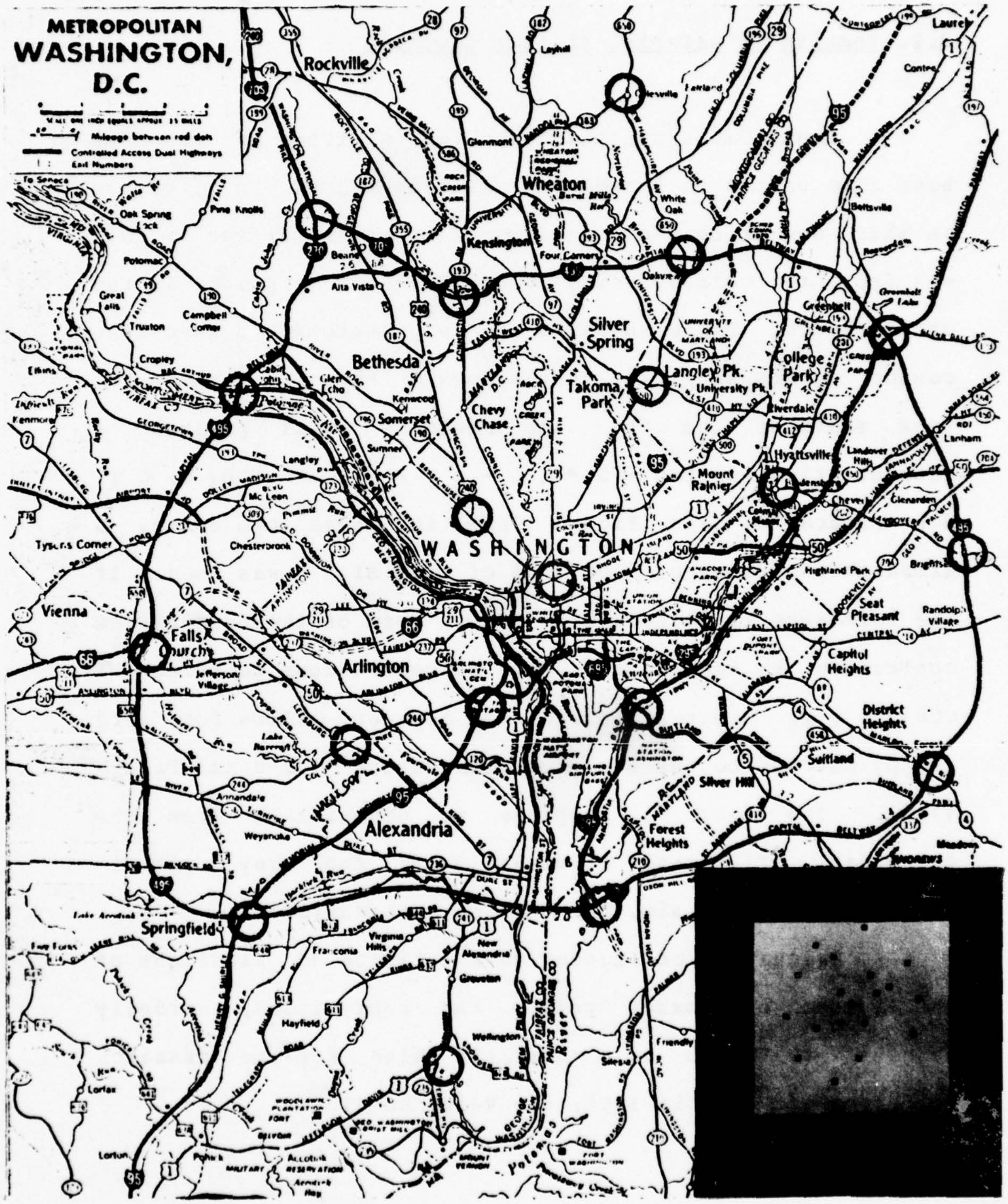


Figure 9b. MAP2 with designated feature points.

3.2. Results of matching similar sketches

Table 2a shows that the two sketches of the tank have five points in common and six near-misses - a situation in which one or both coordinates of one point differ by only +-1 from the corresponding coordinates of a point in the other sketch. Table 9b shows the map sketches to have five common points and five near-misses. Matching either the tank sketches or the map sketches will produce a concentration of ten - 5 * (5 - 1) / 2 - at CCD(0, 0); see Figure 10a and Figure 11a. In these two cases, a mismatch tolerance of 0.00 (0% of grid size) was used. If the tolerance is increased to 0.05, some of the near-misses contribute to the cluster of concentrations centered at CCD(0, 0). Greater tolerances, however, allow for very sloppy matches to be accepted; see Figure 10c-d and Figure 11c-d. Too large a response is undesirable from the standpoint of having to disambiguate too many multiple possible matchings via, for example, relaxation.

Evaluation of Figure 10 and Figure 11 ,in light of the number of common points and near-misses, strongly suggests that 0.05 is a suitable value for the mismatch tolerance and was, in fact, the value used.

TANK1			TANK2		
X	Y	JT	X	Y	JT
14	29	0	14	29	0
19	24	0	18	24	0
10	20	0	9	21	0
13	20	0	13	21	0
21	20	0	20	20	0
21	19	0	23	18	0
23	18	0	7	16	0
10	17	0	13	14	0
16	17	0	22	11	0
13	14	0	16	8	0
15	10	0	6	6	0
11	9	0	12	5	0
6	6	0	20	4	0
18	6	0	-99	-99	0
7	5	0			
20	4	0			
-99	-99	0			

Table 2a. TANK1/TANK2 point-data.

MAP1			MAP2		
X	Y	JT	X	Y	JT
10	28	3	18	31	2
12	27	3	10	28	3
21	27	5	20	20	5
23	27	4	13	26	5
9	26	3	25	25	4
26	25	4	7	23	4
9	24	2	19	23	4
8	23	5	22	21	5
10	23	3	14	20	2
27	21	4	27	19	5
6	20	5	16	18	6
23	19	6	5	16	2
14	17	6	14	15	3
5	16	2	18	15	5
15	16	5	10	14	4
18	16	3	26	13	4
16	15	4	7	9	4
18	15	5	17	9	2
7	9	4	13	5	3
17	9	2	-99	-99	0
-99	-99	0			

Table 2b. MAP1/MAP2 point-data.

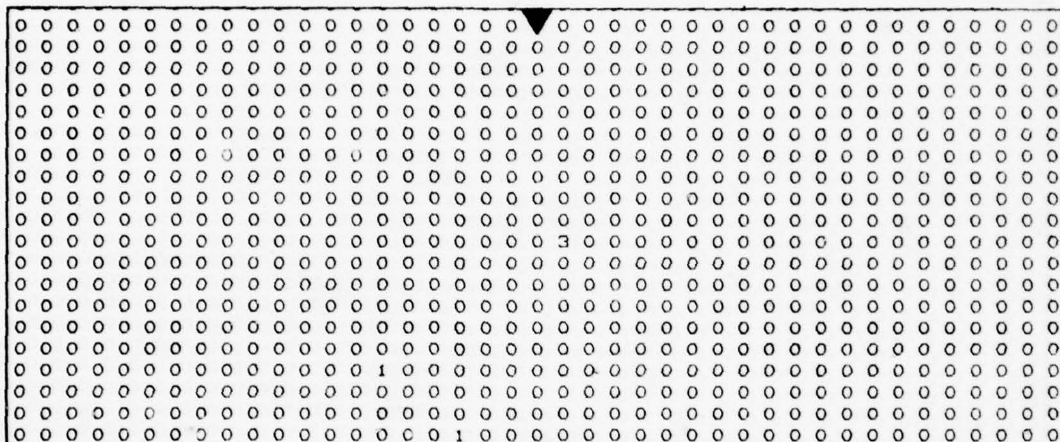


Figure 10a. TANK1 vs. TANK2 with mismatch tolerance 0.00.

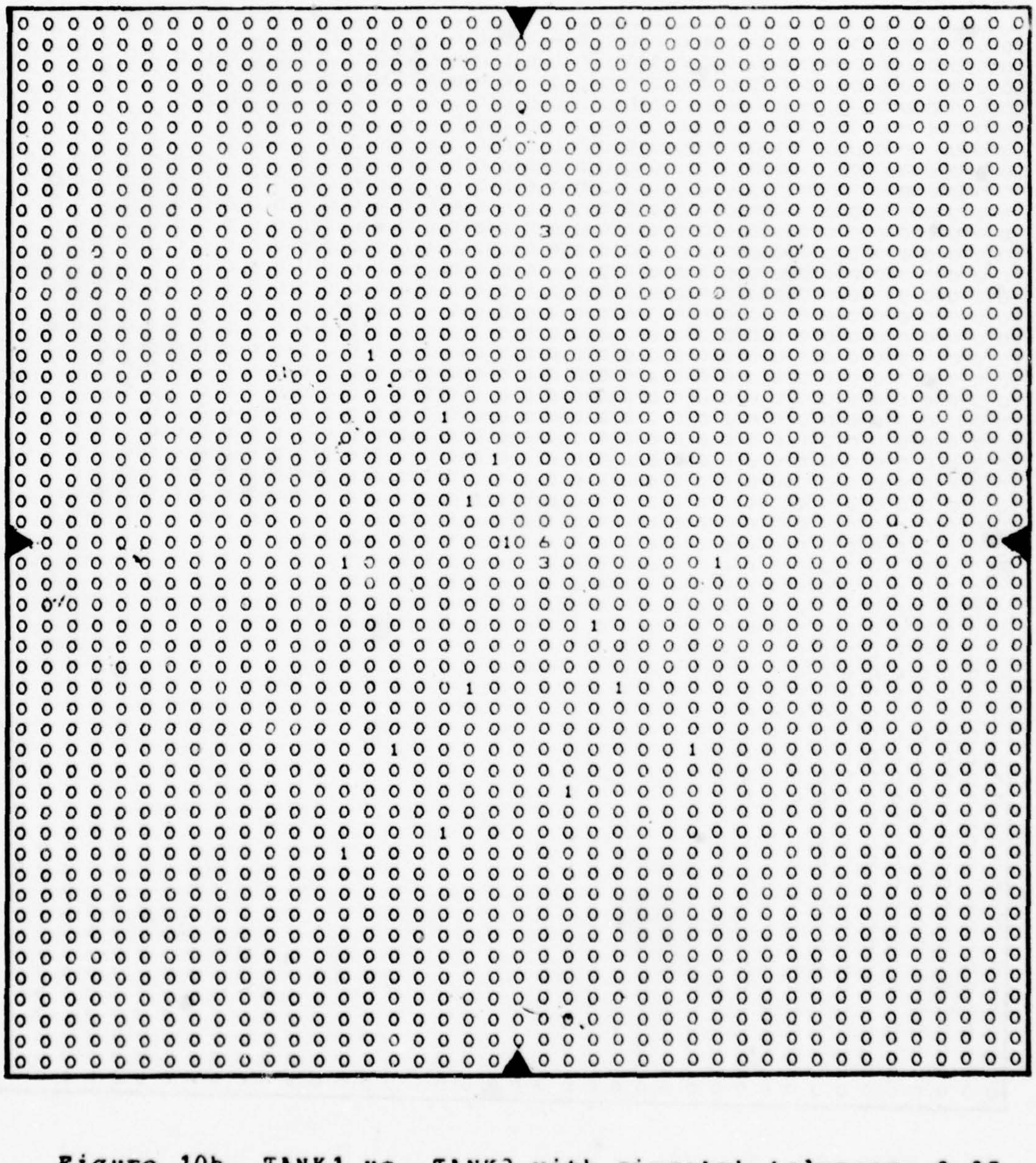


Figure 10b. TANK1 vs. TANK2 with mismatch tolerance 0.05.

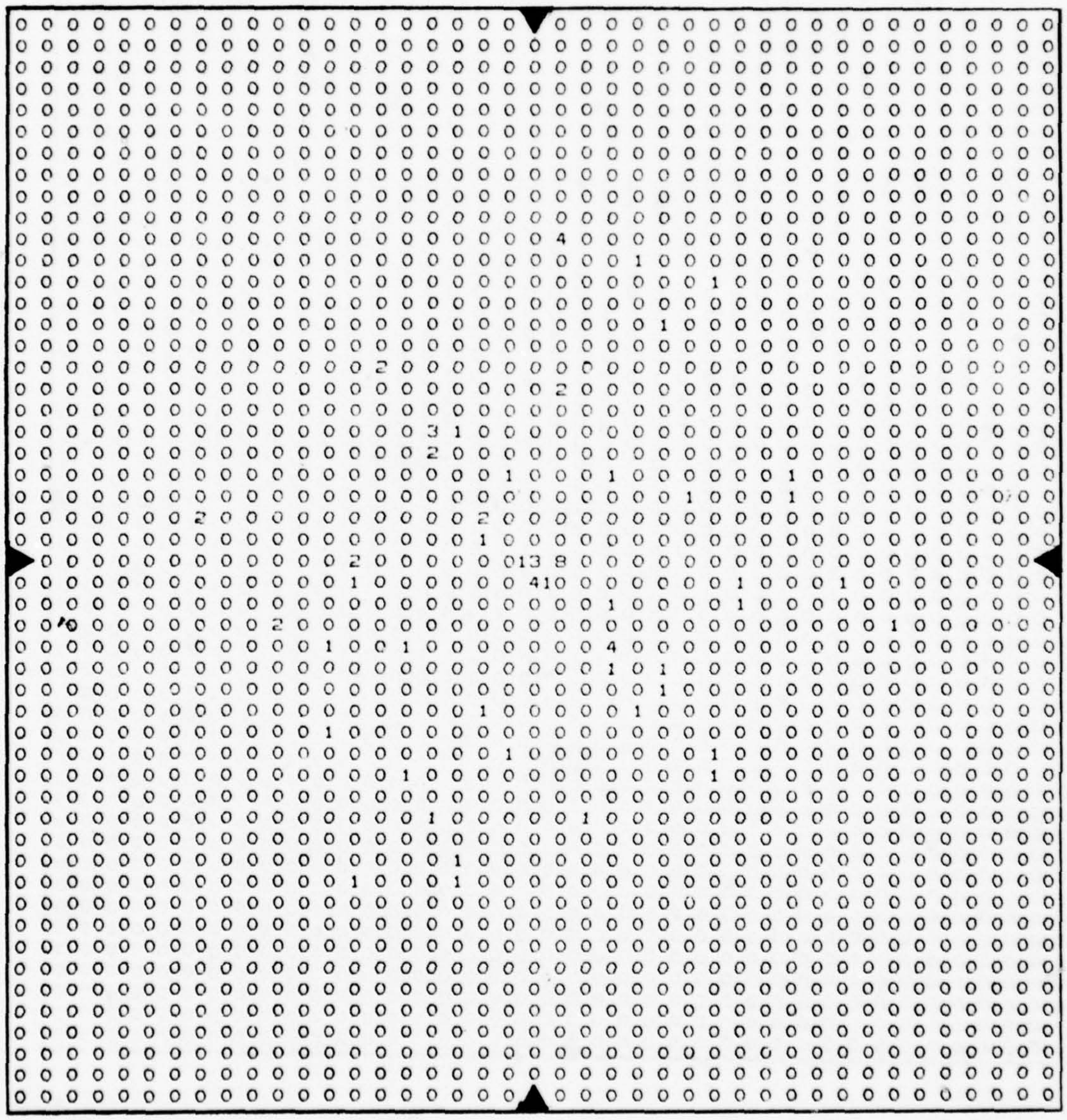


Figure 10c. TANK1 vs. TANK2 with mismatch tolerance 0.10.

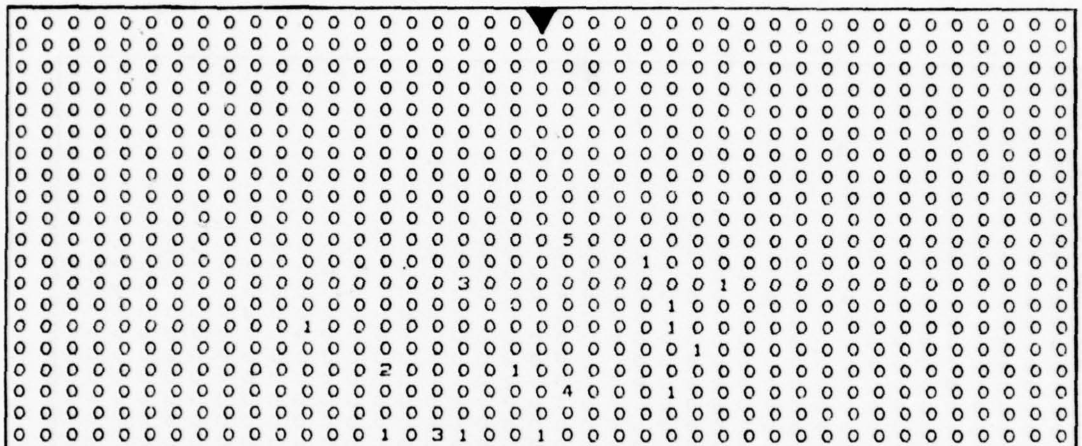


Figure 10d. TANK1 vs. TANK2 with mismatch tolerance 0.15.

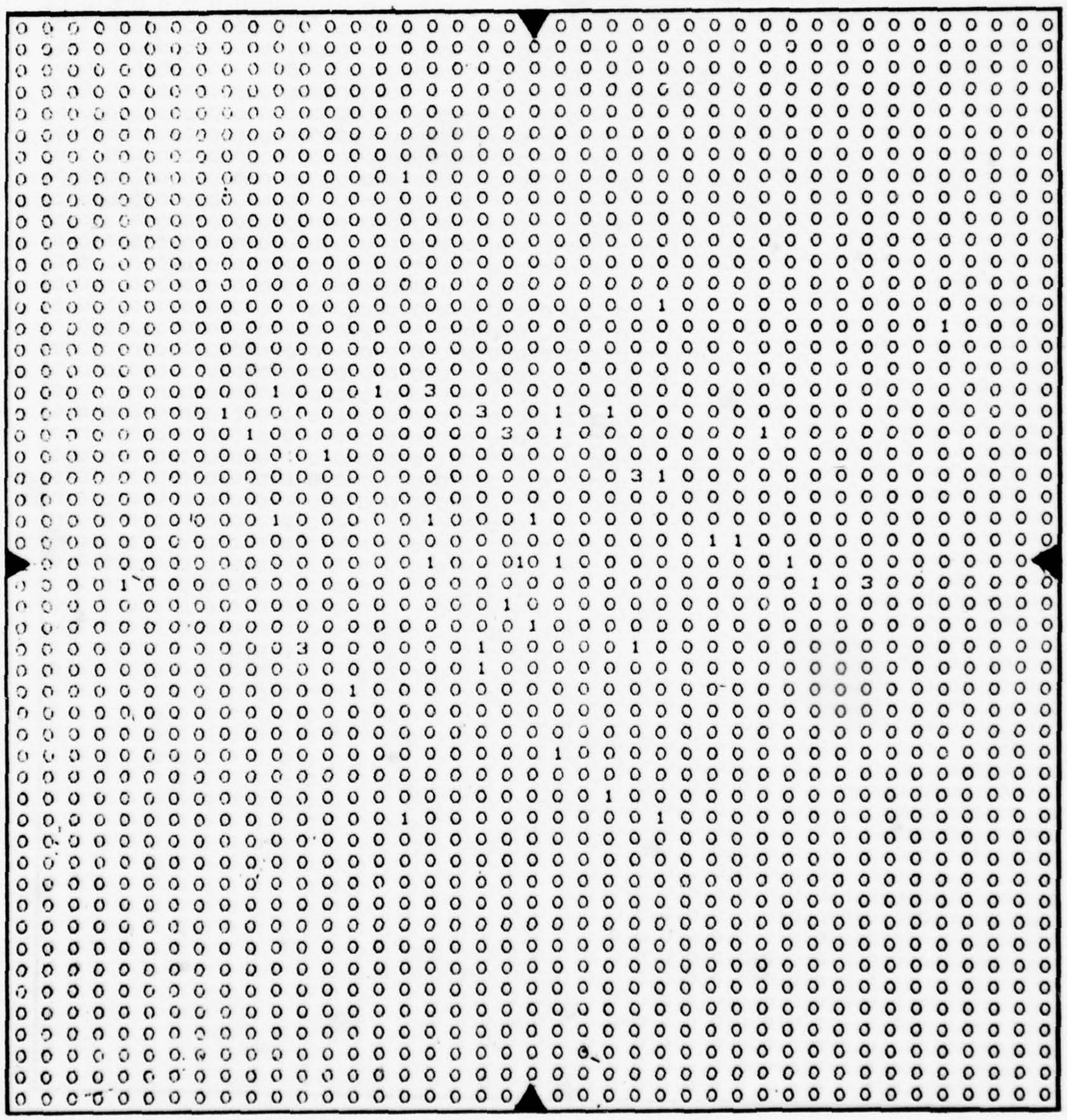


Figure 11a. MAP1 vs MAP2 with tolerance 0.00.

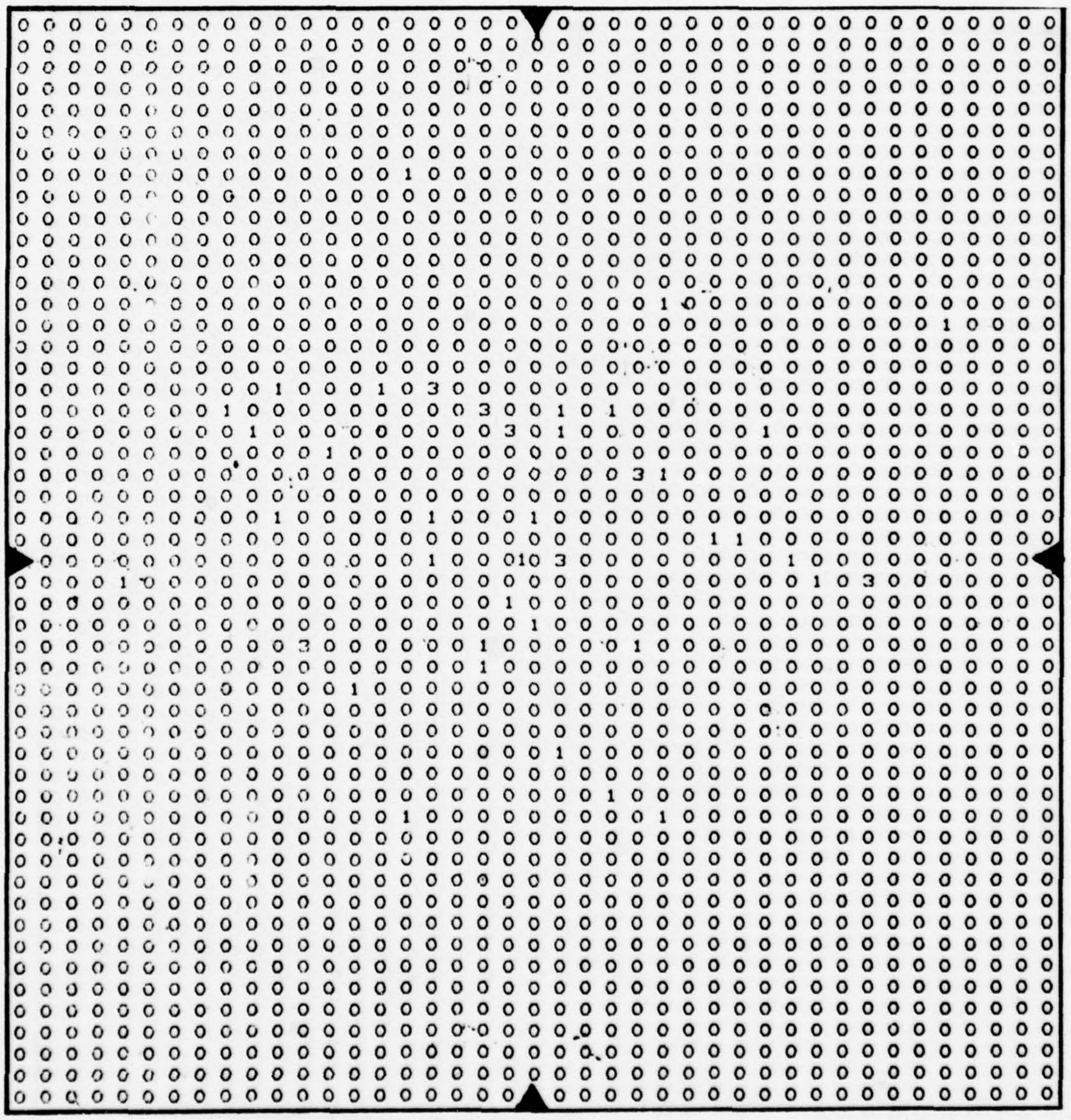


Figure 11b. MAP1 vs MAP2 with tolerance 0.05.

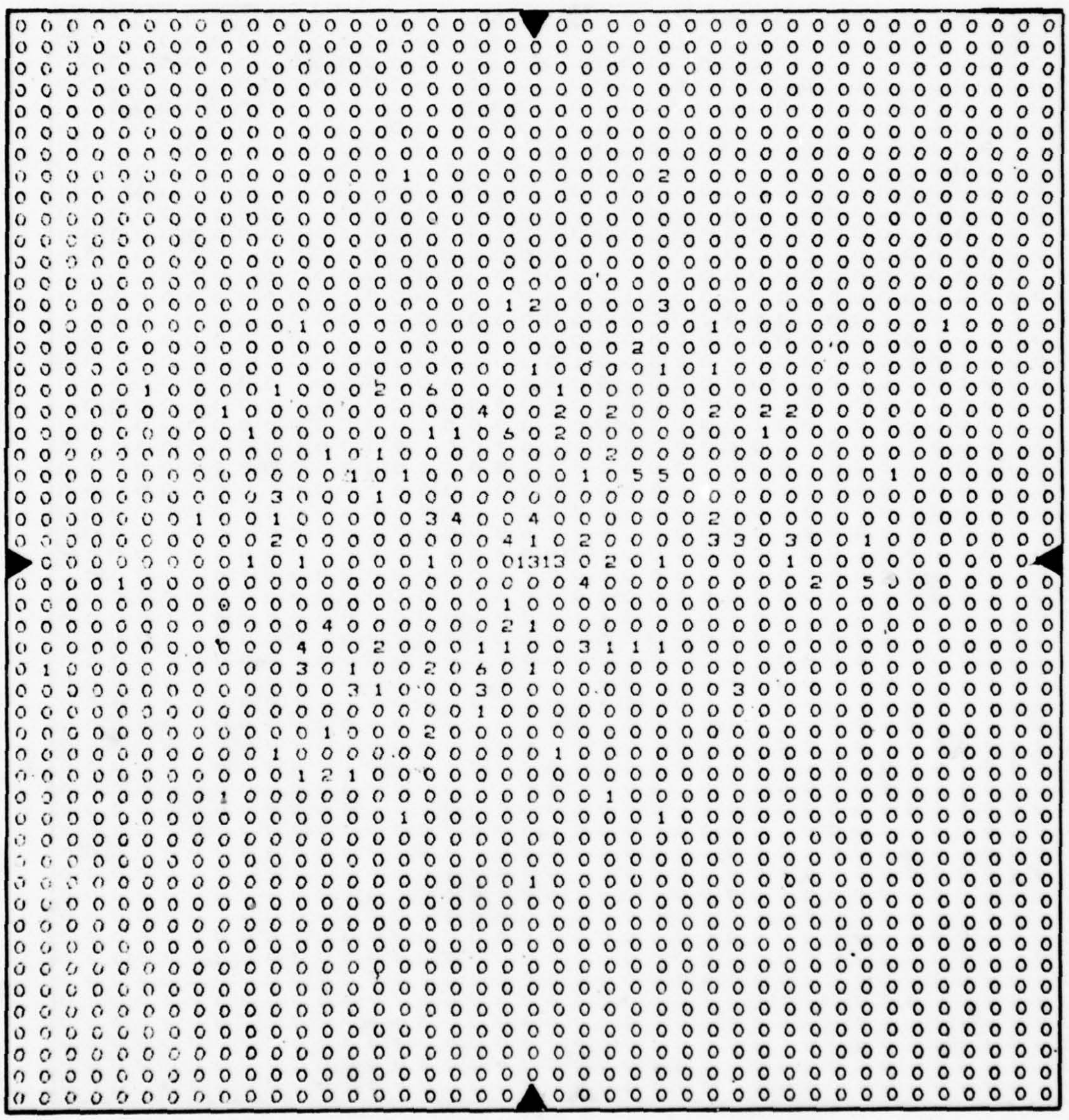


Figure 11c. MAP1 vs MAP2 with tolerance 0.10.

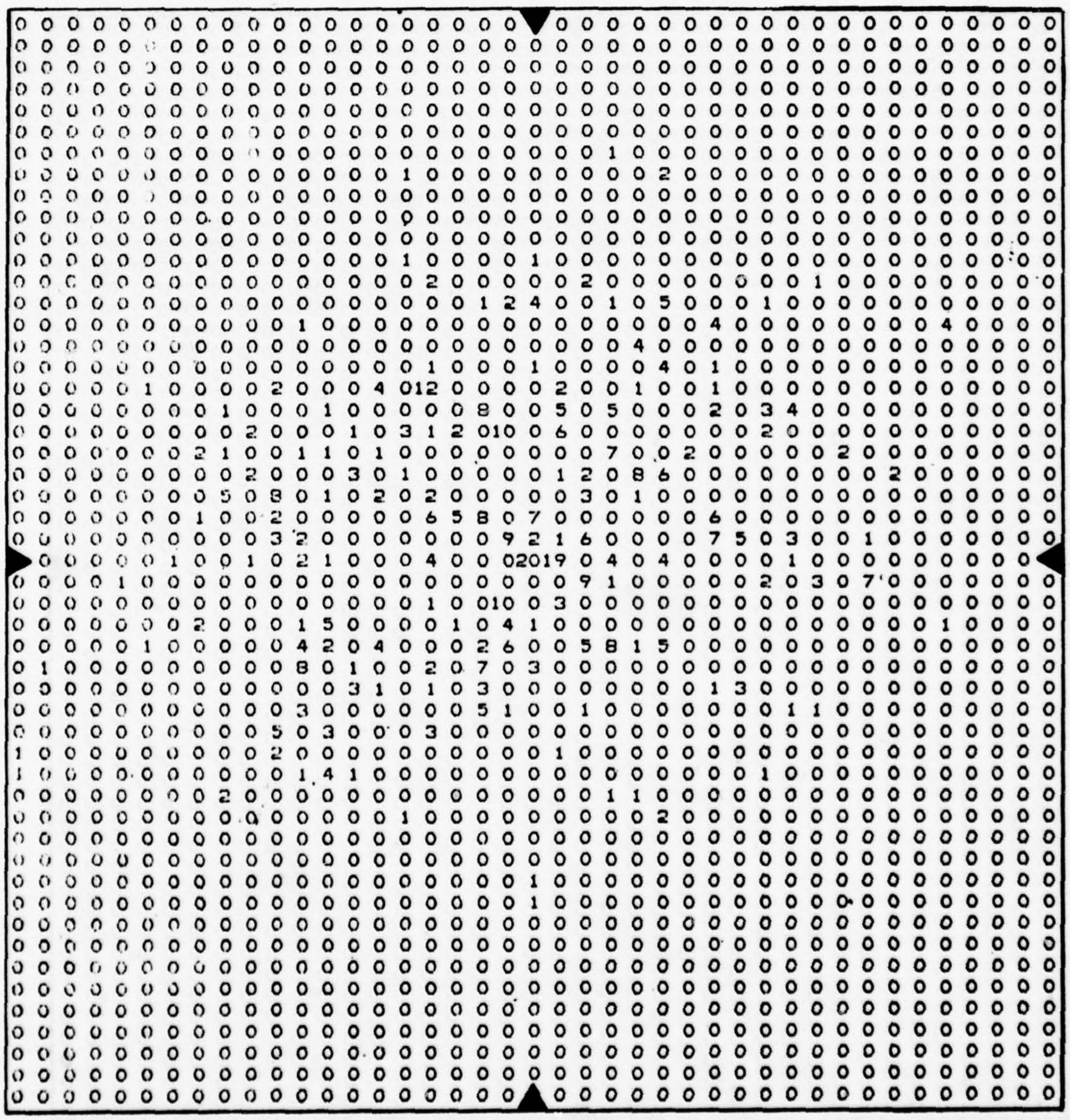


Figure 11d. MAP1 vs MAP2 with tolerance 0.15.

3.3. Effects of noise on matching

To determine the robustness of the matching algorithm, varying amounts of different types of noise were added to copies of the MAP2 sketch. The following types of noise were considered:

(1) Brownian-type motion - Section 3.3.1,

(2) rotation - Section 3.3.2,

(3) rescaling - Section 3.3.3, and

(4) random addition(s)/deletion(s) - Section 3.3.4.

Each section presents the expected results first and then evaluates the actual results in terms of those expectations.

3.3.1. Brownian-type motion noise effects

Four mutated copies of MAP2 were produced by moving each point one unit (3.125% of the sketch size), two units (6.25%), four units (12.5%), and eight units (25%), respectively, in one of eight randomly selected directions - labelled 0 through 7 - as illustrated in Figure 12. Note: "*" indicates the location from which a point is moved.

Table 3 defines the relative point pair movement possibilities. Each possibility is one of six events listed below. One point of an arbitrary pair moves in the

3	2	1
4	*	0
5	6	7

Figure 12. Directions of possible point movement.

Movement Direction -> ↓	0	1	2	3	4	5	6	7
0	E1	E2	E4	E5	E3	E5	E4	E2
1	E2	E1	E2	E3	E5	E6	E5	E3
2	E4	E2	E1	E2	E4	E5	E3	E5
3	E5	E3	E2	E1	E2	E3	E5	E6
4	E3	E5	E4	E2	E1	E2	E4	E5
5	E5	E6	E5	E3	E2	E1	E2	E3
6	E4	E5	E3	E5	E4	E2	E1	E2
7	E2	E3	E5	E6	E5	E3	E2	E1

Table 3. Relative point movements.

direction indicated by the column headings. The other point moves as indicated by the row headings.

The six possible events define the

Length-Factor-Change(LFC)-in-distance between two arbitrary points as a result of the unit movement of each. Those events and frequencies of occurrence are:

(1) E1 - 0 unit LFC, 8 times (out of 64),

(2) E2 - 1 unit LFC, 16 times,

(3) E3 - 2 units LFC, 12 times,

(4) E4 - SQRT(2) units LFC, 8 times,

(5) E5 - SQRT(5) units LFC, 16 times, and

(6) E6 - 2*SQRT(2) units LFC, 4 times.

The percent of grid size change of the six events and various Brownian movement distances are listed in Table

Brownian distance -> / LFC ↓	0	1	2	4	8
0	0.000	0.000	0.000	0.000	0.000
1	0.000	3.125	6.250	12.500	25.000
2	0.000	6.250	12.500	25.000	50.000
2**0.5	0.000	4.419	8.838	17.676	35.352
5**0.5	0.000	6.988	13.976	27.952	55.904
2*2**0.5	0.000	8.839	17.678	35.356	70.712

Table 4. Percents of grid size for various LFC's/distances.

4; if each point moves distance D, then the distance change

is D * LFC.

If a sketch is matched against itself, obviously a concentration of value N (N-1) / 2 (Maximum Expected Concentration) will occur at CCD(0, 0);however, other extraneous concentrations may also occur. When a sketch is matched against a copy which has undergone Brownian movement, one may expect the following concentrations:

(1) 0 - MEC*1 at (0,0)

(2) 1 - MEC*1/8 at (0,0) + NXM*1/4 at (+-1,+-1) + NXM*1/8 at (+-SQRT(2),+-SQRT(2))

(3) 2 - MEC*1 at (0,0)

(4) 4 - MEC*1 at (0,0)

(5) 8 - MEC*1 at (0,0).

where:

(1) MEC = N (N-1) / 2,

(2) (+-#,+-#) is interpreted as:

(a) CCD(+#,0),

(b) CCD(-#,0),

(c) CCD(0,+#), and

(d) CCD(0,-#).

NOTE: lack of a "+-" means that only one element, CCD(#,#), is designated.

The above expectations are based on the assumption that the pseudo-random number generator will produce a uniform distribution, that is, all eight directions of movement are equally likely; however, the expectations are

subject to the usual probablistic interpretations. Hence, one should expect that only unit distance Brownian movement will yield any significant cluster of concentrations. This is illustrated by Figure 13a-d.

3.3.2. Rotational noise effects.

Six rotated versions of MAP2 were produced by rotations of:

(1) 5 degrees,

(2) 10 degrees,

(3) 15 degrees,

(4) 20 degrees,

(5) 25 degrees, and

(6) 30 degrees.

The point closest to an "eyeball estimate" of the centroid of MAP2 was chosen to be the origin of rotation in all cases.

Effects of rotational noise can be predicted in the following manner. Consider two points which are unit distance apart. If the imaginary line segment connecting the points is duplicated and rotated as above, one can compute the length of the third side of the imaginary triangles thus produced. Recall that mismatch tolerance, defined in terms of grid size, limits how long the imaginary

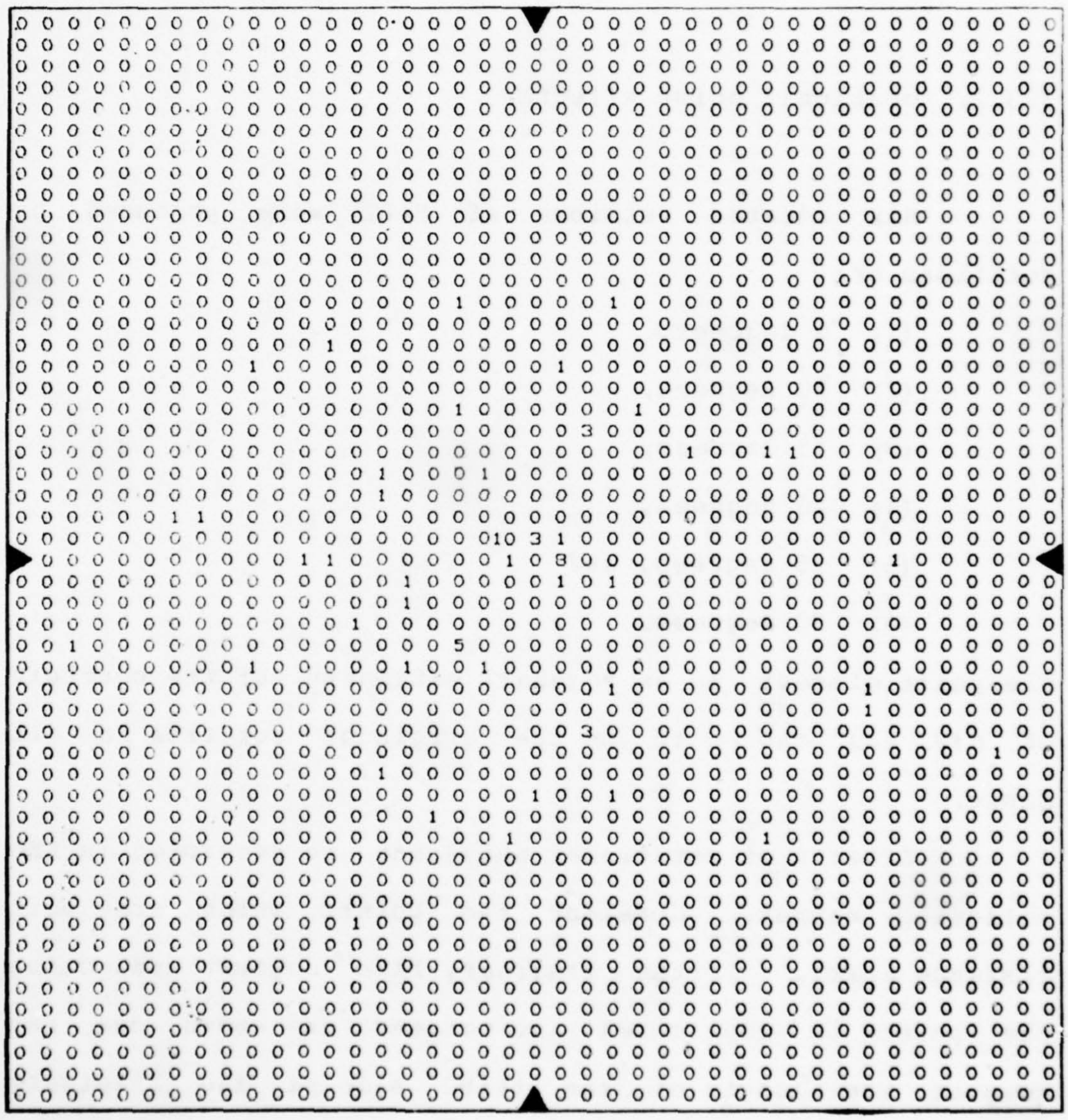


Figure 13a. MAP2 vs. MAP2.B1 with tolerance 0.05.

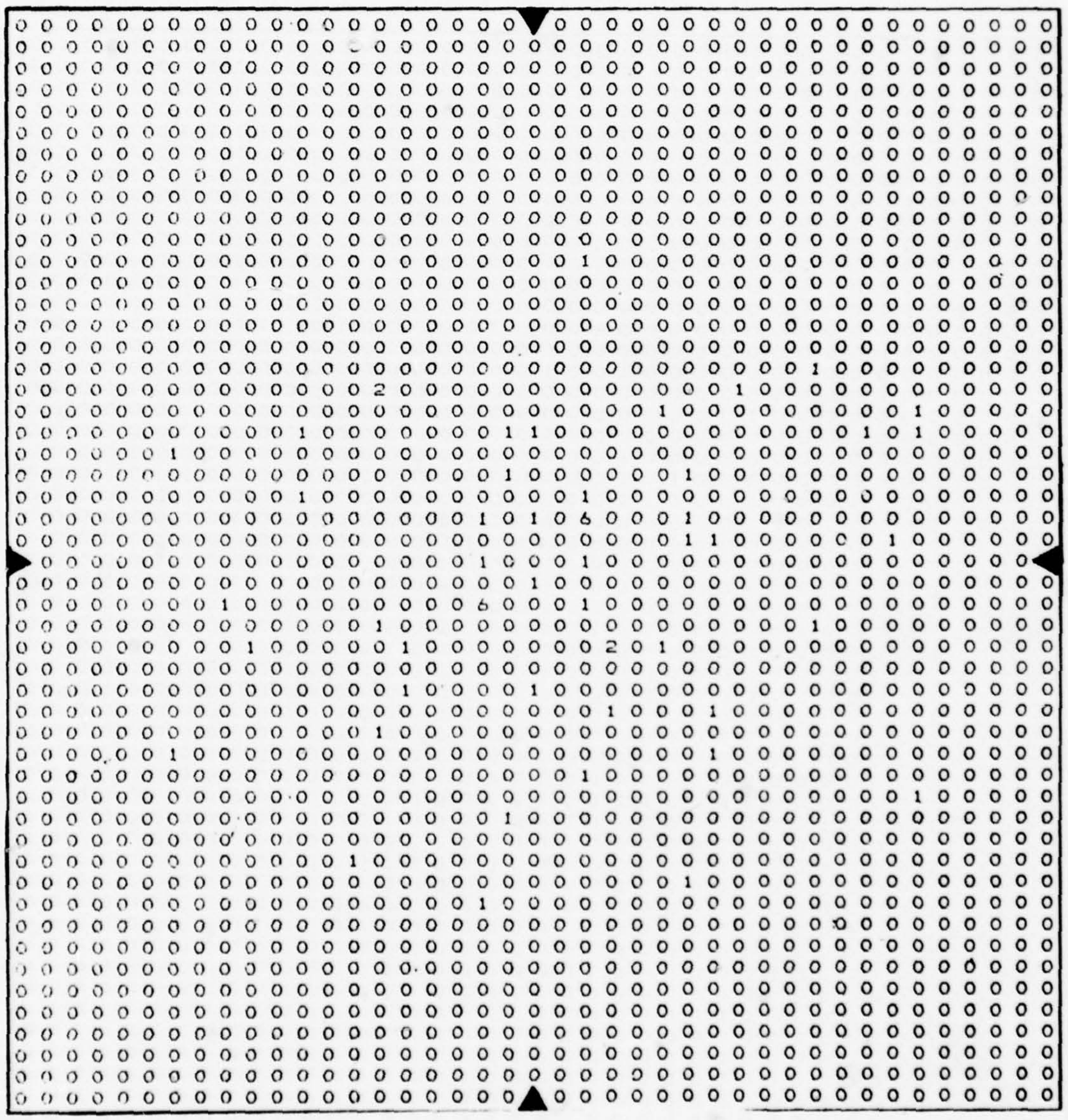


Figure 13b. MAP2 vs. MAP2.B2 with tolerance 0.05.

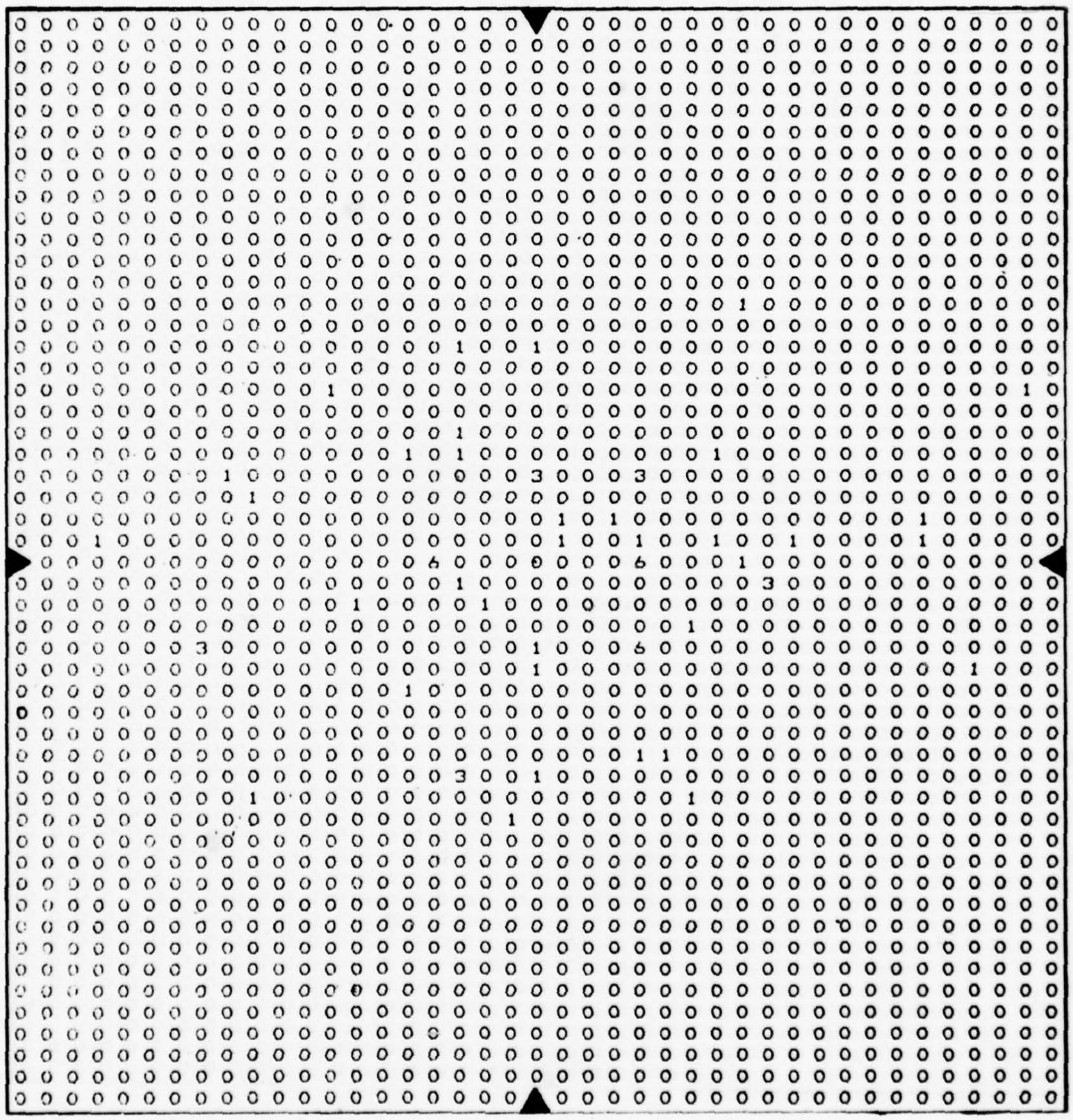


Figure 13c. MAP2 vs. MAP2.B4 with tolerance 0.05.

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```

Figure 13d. MAP2 vs. MAP2.B8 with tolerance 0.05.

third side may be before causing rejections as a possible match. Percents of grid size change are then computable

Degrees	Length of 3rd side	Grid size percent
5	0.08723	8.723
10	0.17431	17.431
15	0.26105	26.105
20	0.43287	43.287
25	0.51763	51.763

Table 5. Percents of grid size for various rotations.

from these as tabulated in Table 5. Noting the percentages, one would expect to achieve significant concentrations only for a rotation of 5 degrees. Figure 14a-f shows this to be true.

3.3.3. Rescaling noise effects.

Five rescaled copies of MAP2 were generated by rescaling point coordinates by the following factors:

(1) 1.01 (NOTE: this produced no change in coordinate values),

(2) 1.02,

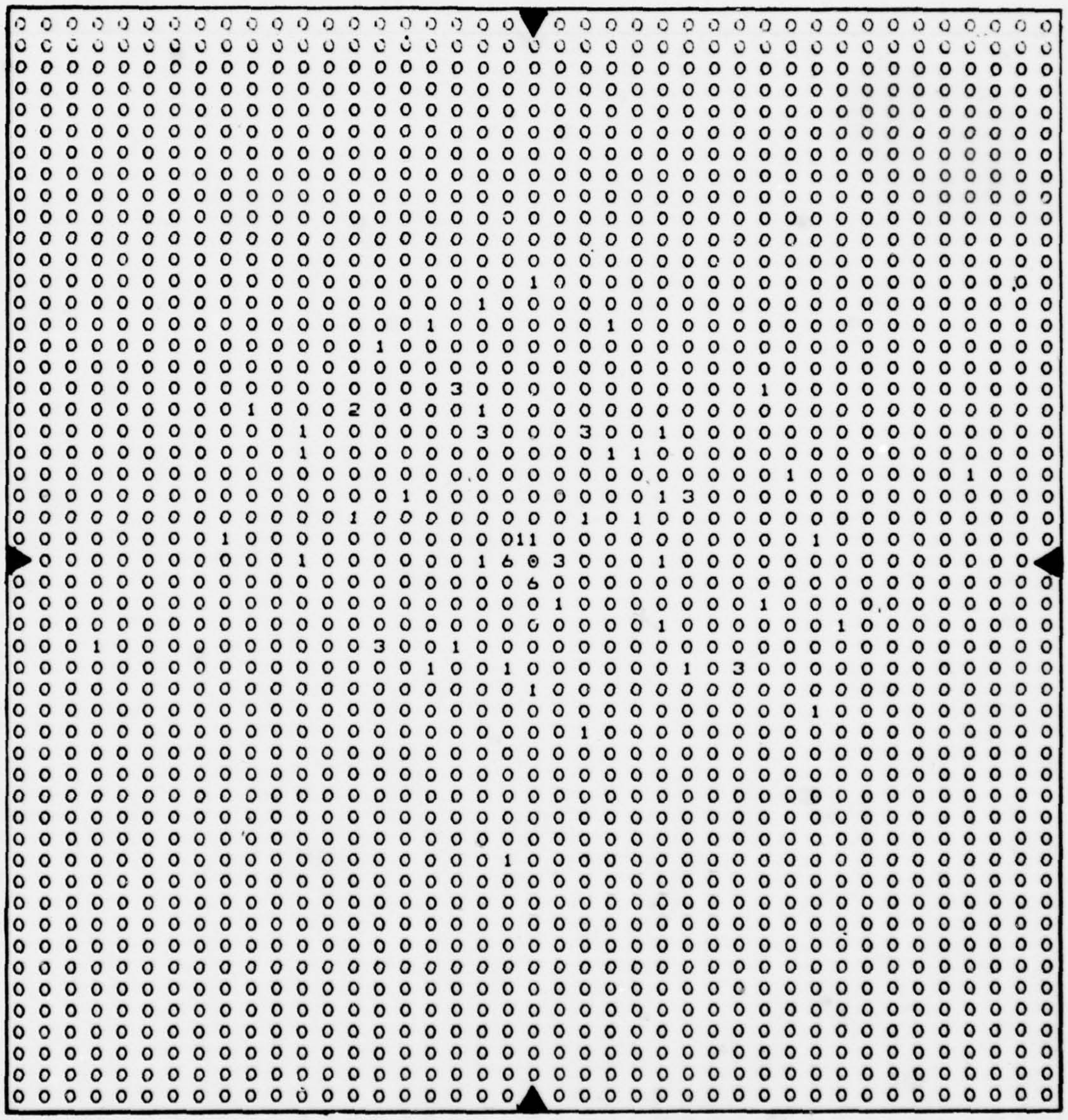

Figure 14a. MAP2 vs. MAP2.R5 with tolerance 0.05.

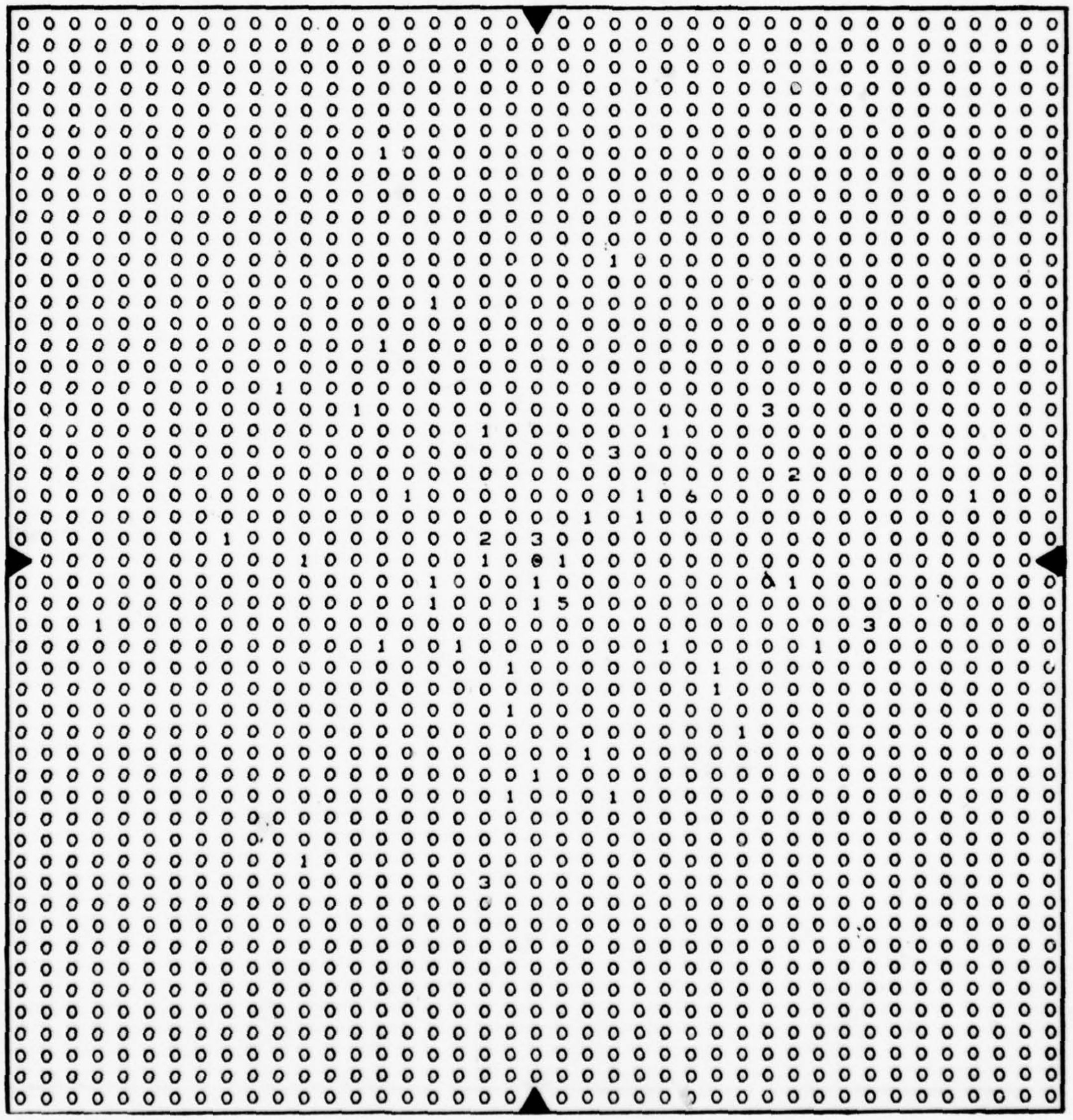

Figure 14b. MAP2 vs. MAP2.R10 with tolerance 0.05.

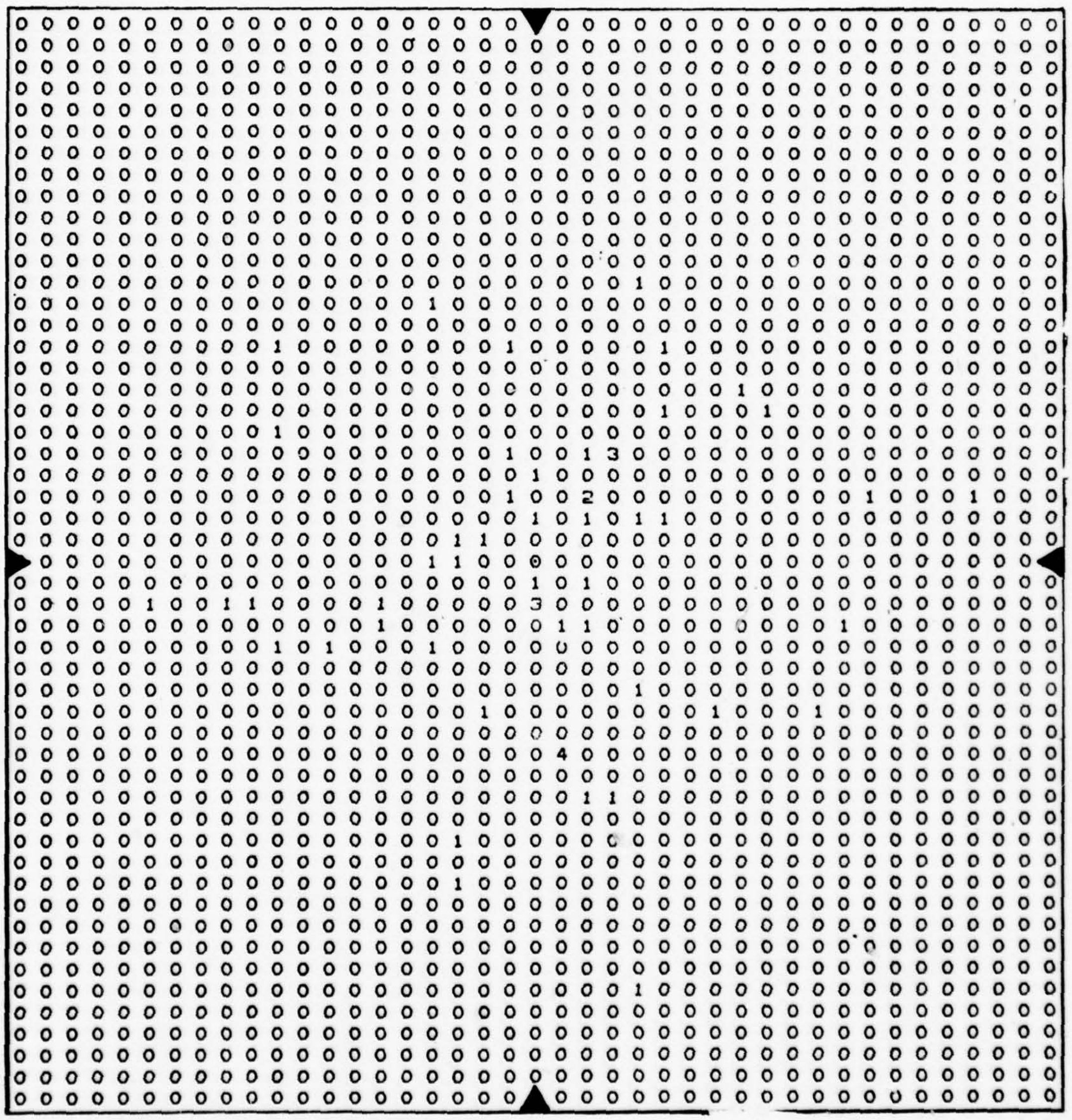

Figure 14c. MAP2 vs. MAP2.R15 with tolerance 0.05.

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0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
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Figure 14d. MAP2 vs. MAP2.R20 with tolerance 0.05.

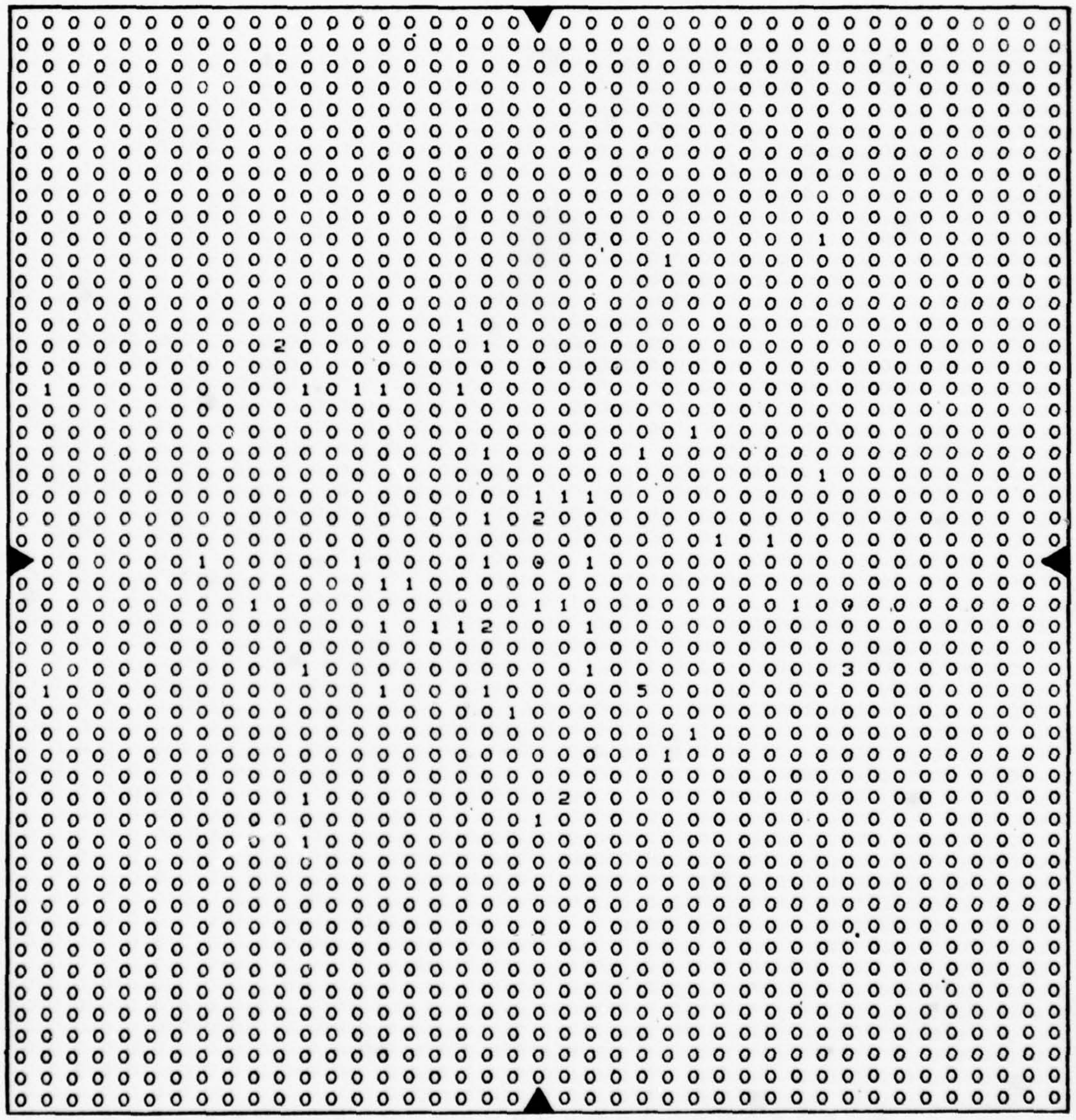

Figure 14e. MAP2 vs. MAP2.R25 with tolerance 0.05.

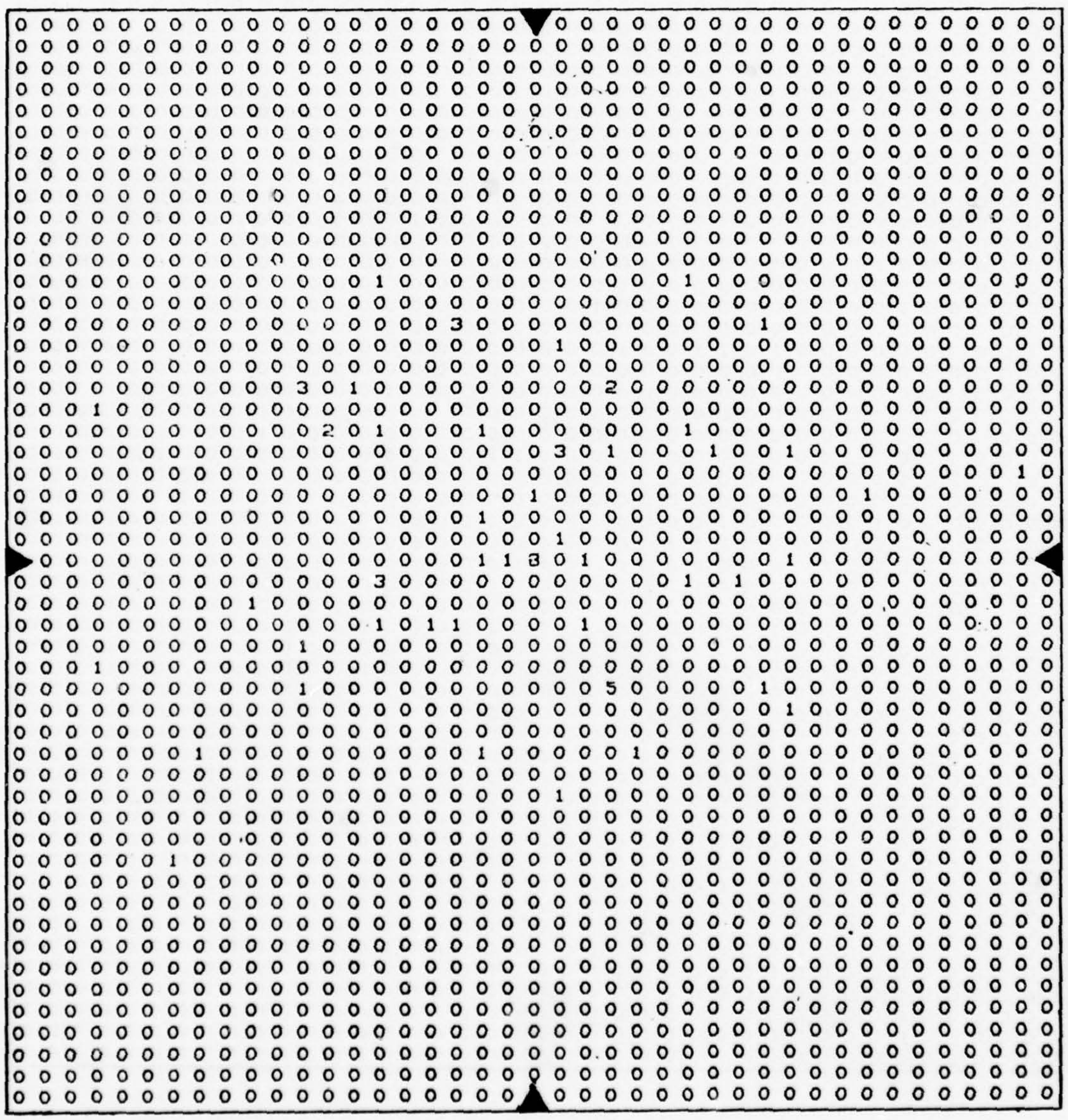

Figure 14f. MAP2 vs. MAP2.R30 with tolerance 0.05.

(3) 1.05,

(4) 1.10, and

(5) 1.20.

Matching results for the above cases are also rather predictable. Since a mismatch tolerance of 0.05 (5%) is allowed, one would expect the cases (1), (2), and (3) to produce significant concentrations. Figure 15a-c shows this to be true. One would also expect cases (4) and (5) to give insignificant responses; however, Figure 15d-e show this to be true only for case (5). The reason for this anomaly is roundoff error which can result in some points being up to SQRT(2) units (4.419%) closer than they should be. Hence, the "unexpected" significant response.

3.3.4. Random additions/deletions noise effects.

Four mutated versions of MAP2 were produced by randomly selecting one, two, four, and eight points for replacement by randomly generated points. Results will be good in all four cases because in each case there will be N (N-1) / 2 (where N is the number of unreplaced points) point pairs which remain exactly the same.

The four cases should produce concentrations of 153, 136, 105, and 55, respectively, at CCD(0, 0). Any deviations would be in the form of higher valued

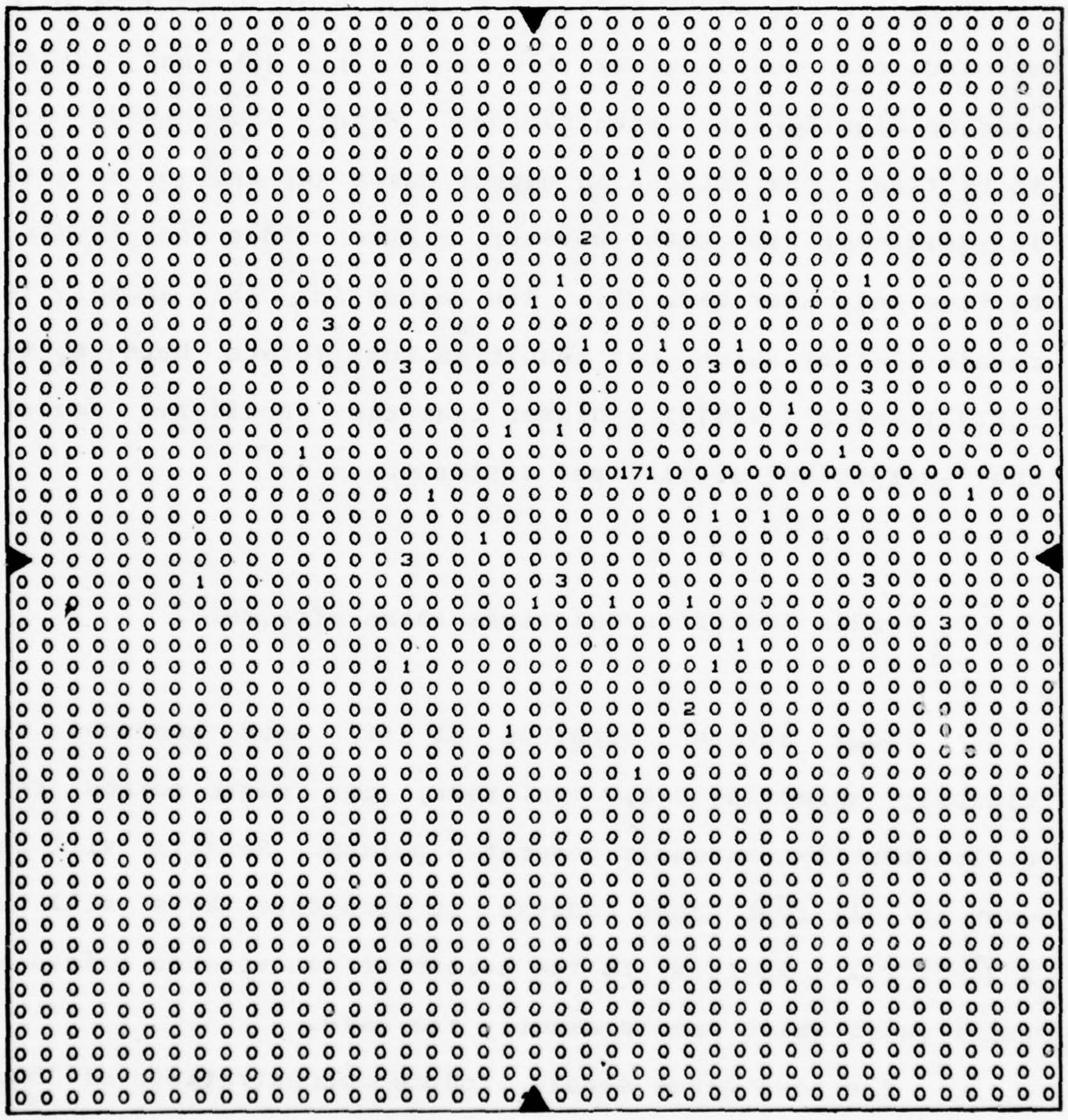

Figure 15a. MAP2 vs. MAP2.S01 with tolerance 0.05.

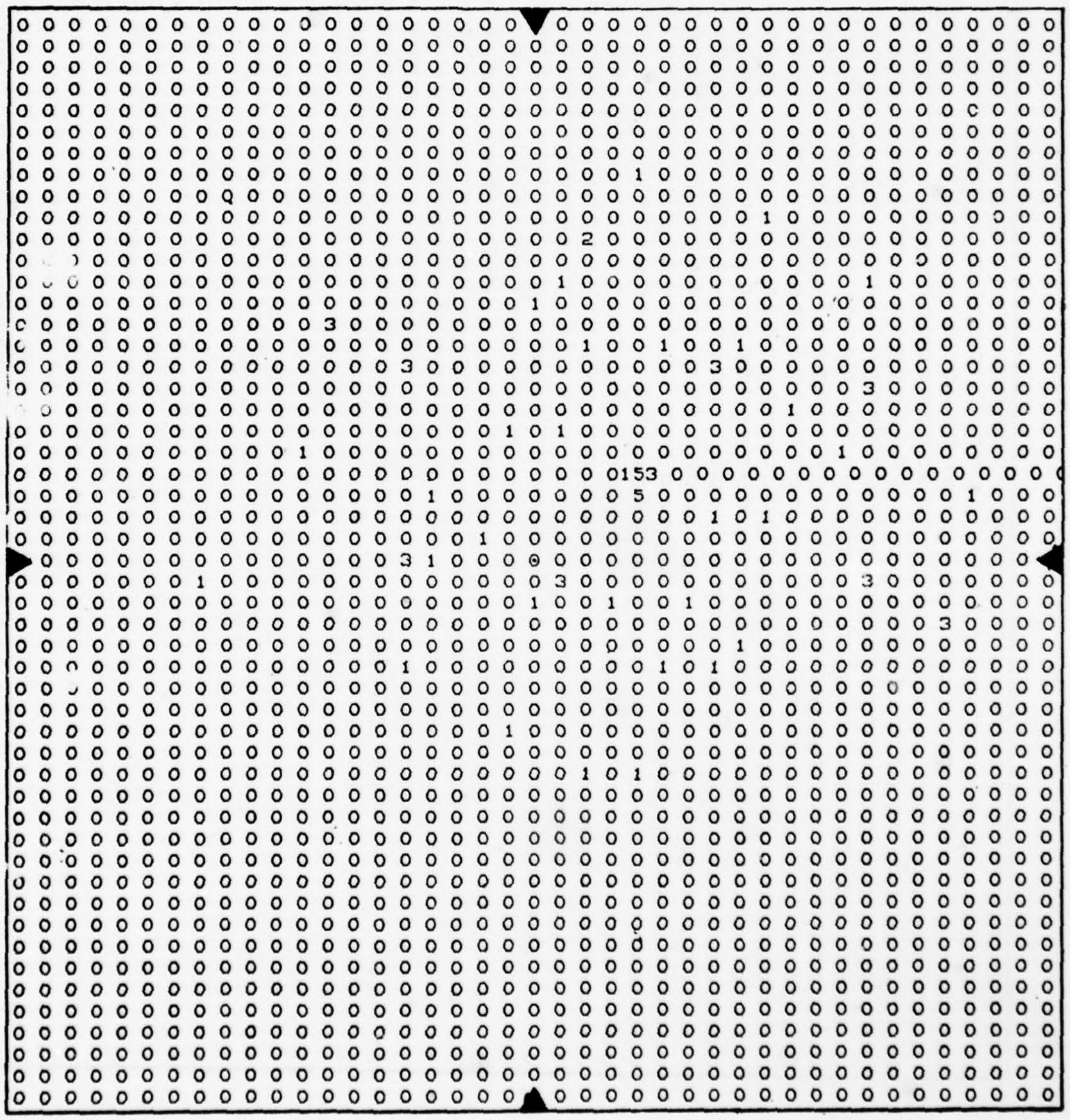

Figure 15b. MAP2 vs. MAP2.S02 with tolerance 0.05.

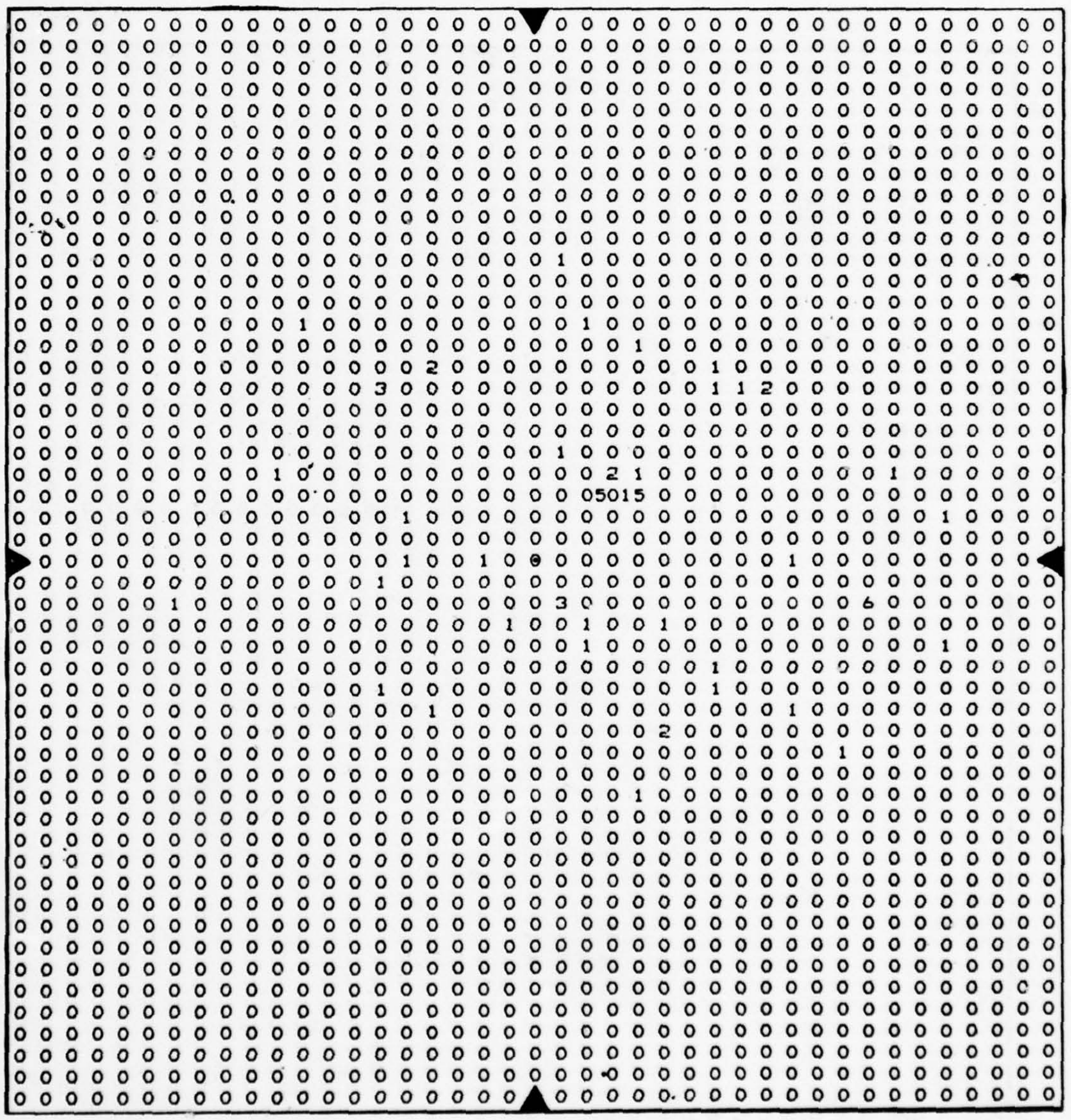

Figure 15c. MAP2 vs. MAP2.S05 with tolerance 0.05.

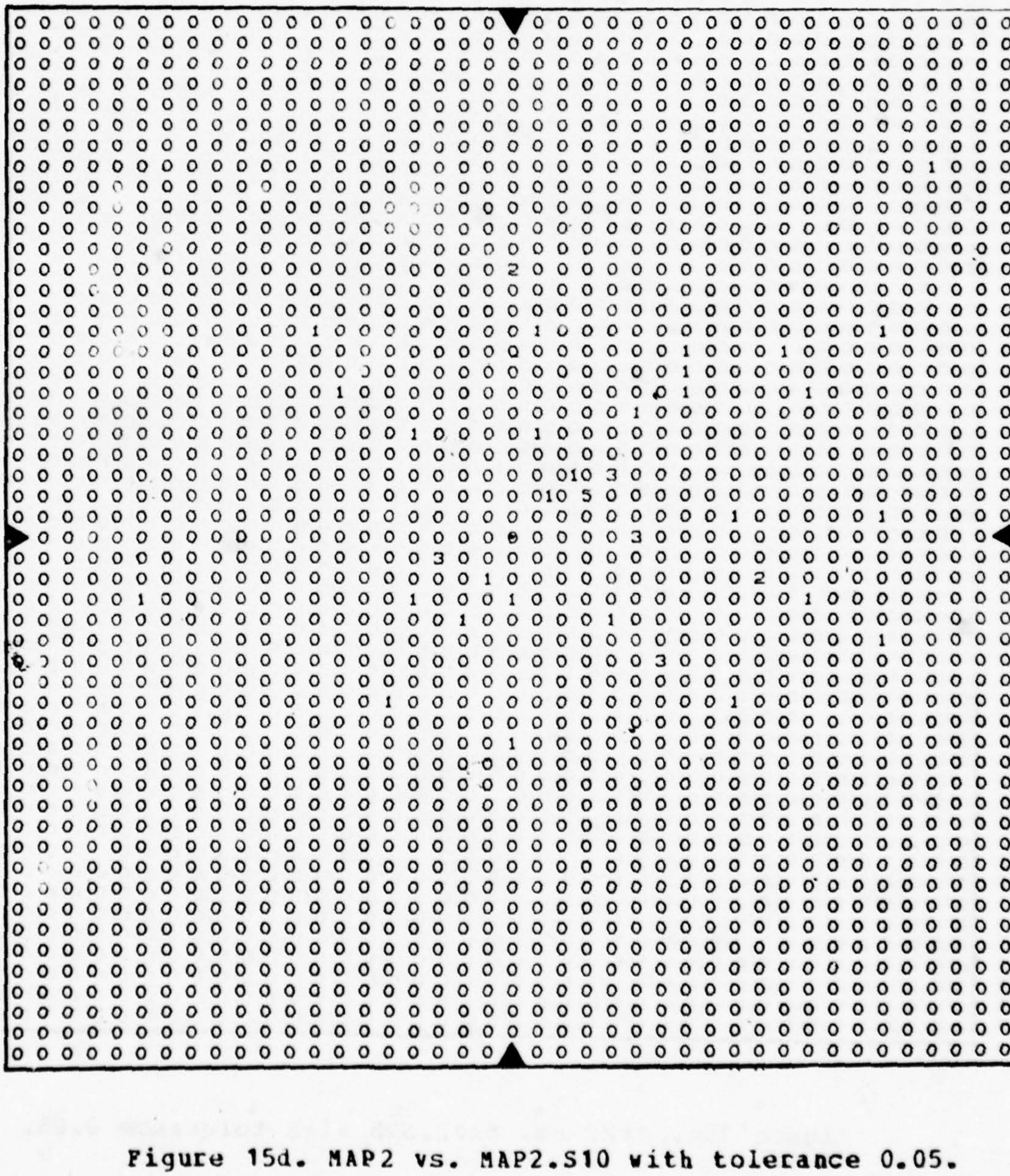

Figure 15d. MAP2 vs. MAP2.S10 with tolerance 0.05.

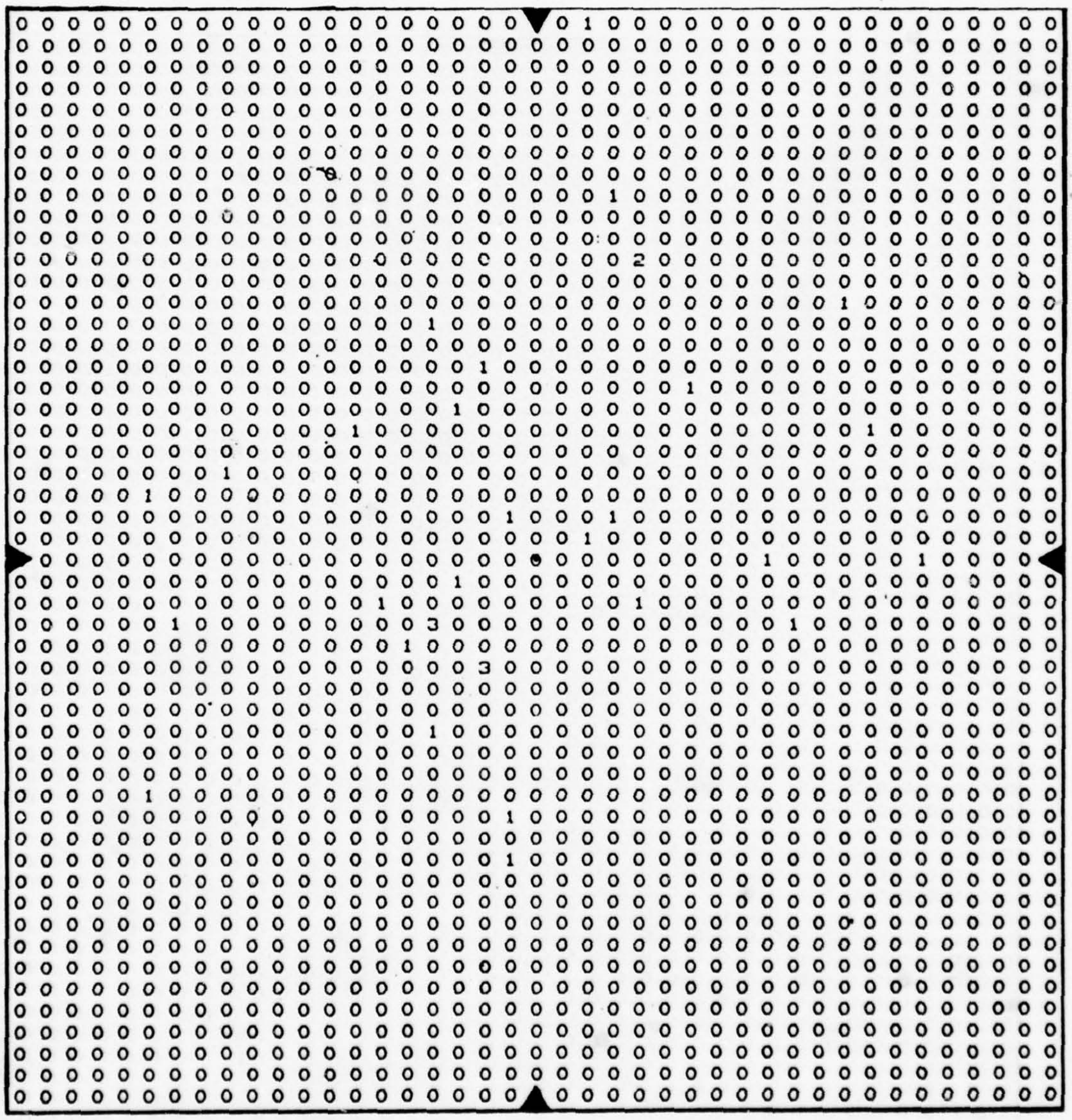

Figure 15e. MAP2 vs. MAP2.S15 with tolerance 0.05.

concentrations due to contributions from the randomly generated points. Figure 16a-d illustrates the accuracy of these expectations.

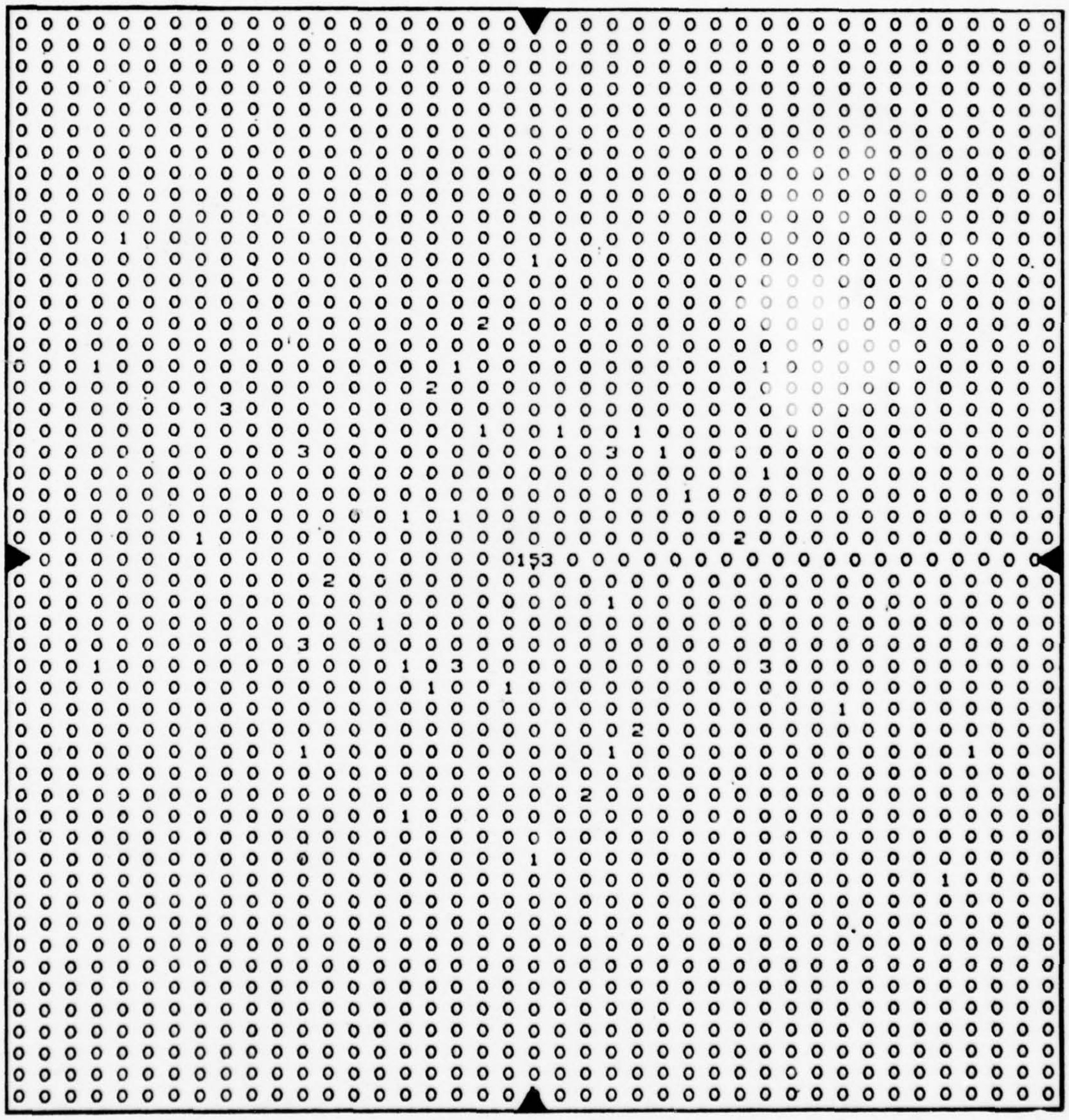

Figure 16a. MAP2 vs. MAP2.AD1 with tolerance 0.05.

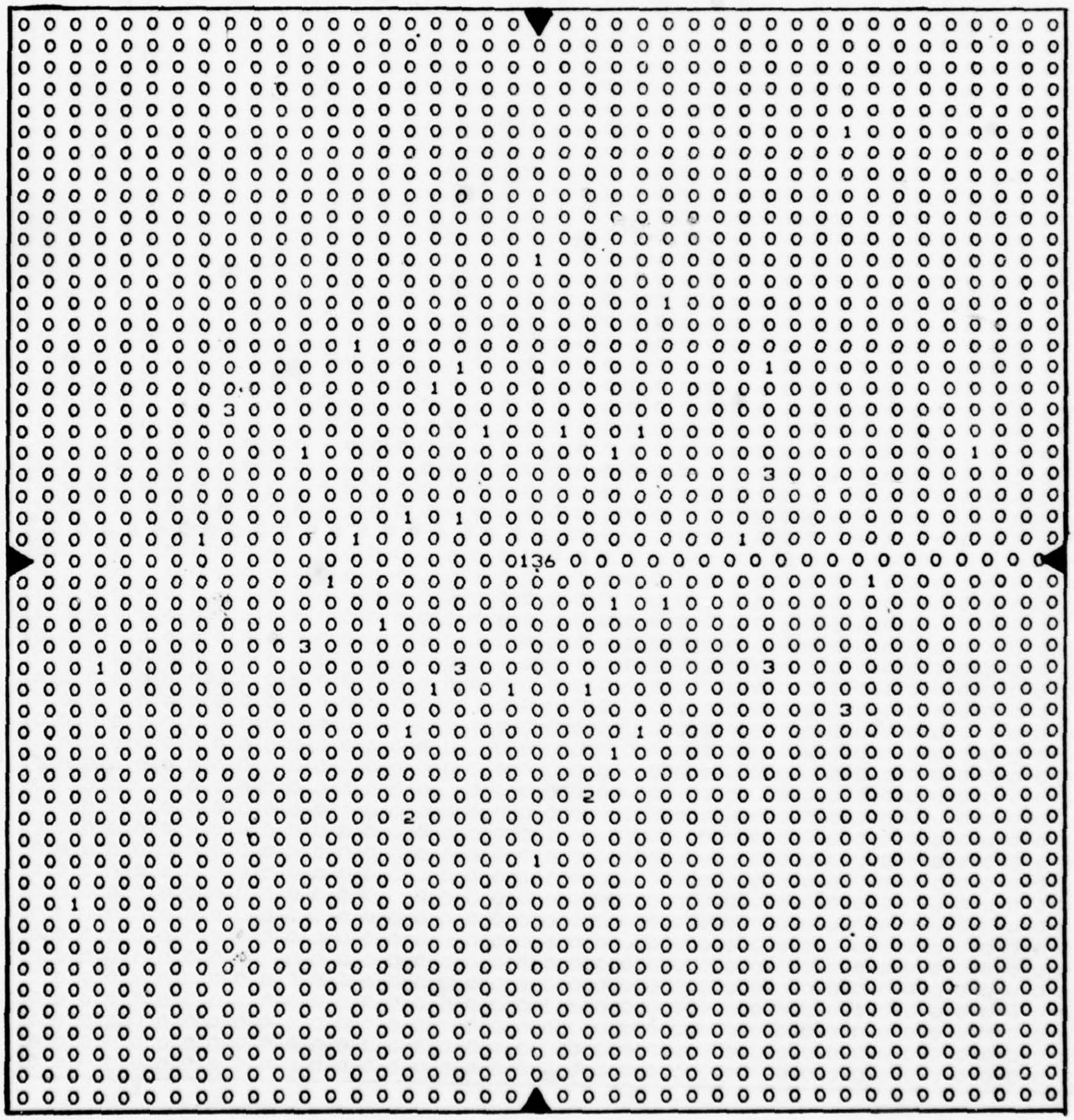

Figure 16b. MAP2 vs. MAP2.AD2 with tolerance 0.05.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
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0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	105	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
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0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
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Figure 16c. MAP2 vs. MAP2.AD4 with tolerance 0.05.

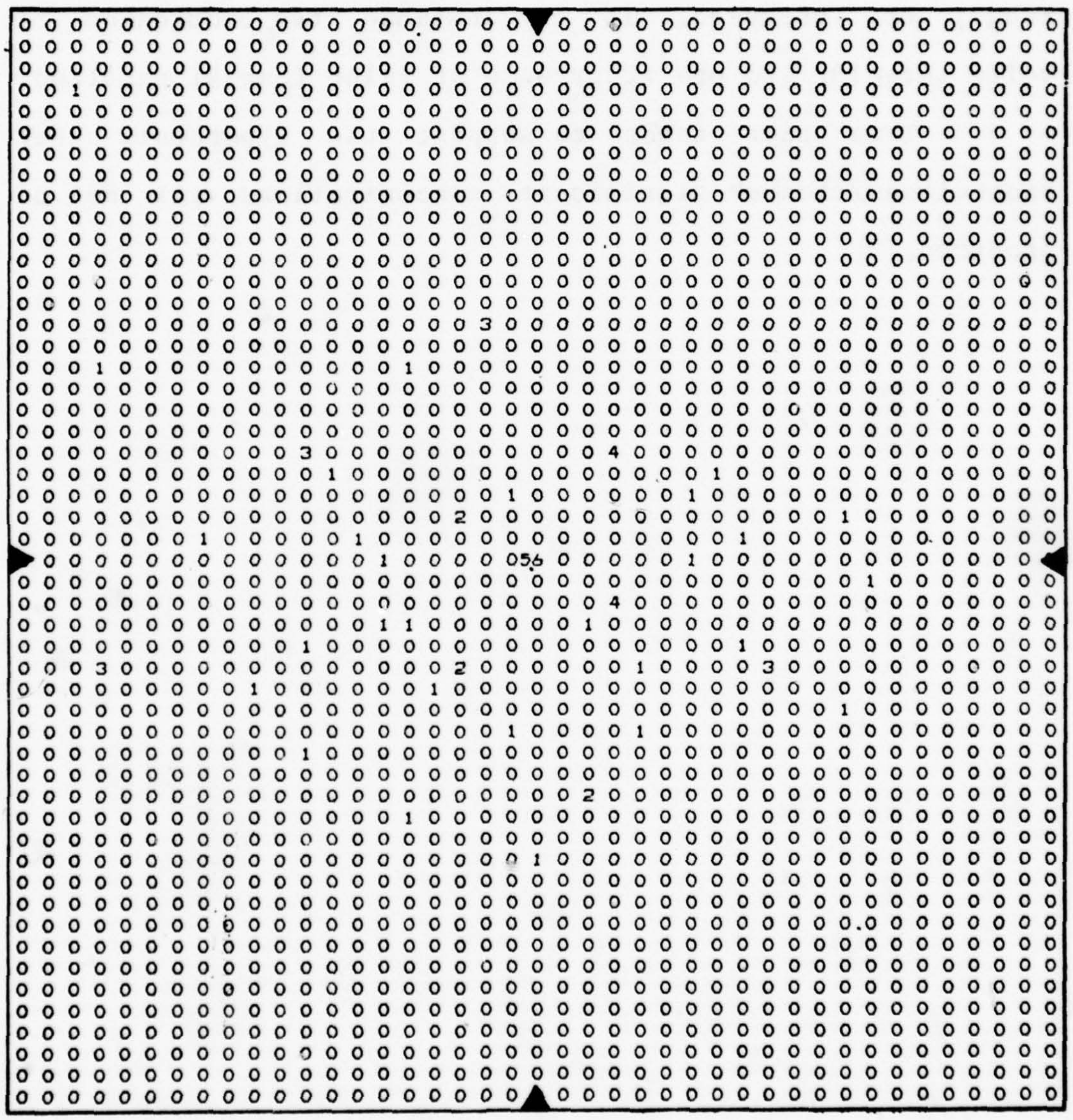

Figure 16d. MAP2 vs. MAP2.AD1 with tolerance 0.05.

3.4. Random point pattern matching

Five random point patterns were generated providing ten pattern combinations. In essentially all cases only very widely scattered "concentrations" of values one(1) or two(2) were produced. In one instance two occurences of value three(3) and one occurrence of value four(4) resulted.

This fact tends to support the hypothesis that "fortuitous/chance" significant concentrations will not be produced.

CHAPTER 4

ENHANCED MATCHING ALGORITHM

This chapter is concerned with describing the various enhancements - some implemented, some not - to the basic PTM/BA algorithm. These enhancements are designed to reduce the effects of the Brownian, rotational, and rescaling noise described in Chapter 3 as well as produce more of the information that would be required to accomplish registration.

Section 4.1 describes why the primary enhancements improve the matching capabilities of PTM/BA. Section 4.2 shows the improved results for the above types of noise and suggests/shows specific ways to further reduce noise effects.

4.1. Basic algorithm enhancements

The primary enhancement to PTM/BA was the use of additional match criteria - junction type (Waltz [W1]) testing. Recalling that each point P(i) is represented by the three-tuple [x(i), y(i), jt(i)], the following requirement was added:

> Let P1(i),P1(j) and P2(i'),P2(j') be two arbitrary points from SKETCH1 and SKETCH2, respectively. Then:
>
> (1) If P1.jt(i) = P2.jt(i') AND P1.jt(j) = P2.jt(j'), or
>
> (2) If P1.jt(i) = P2.jt(j') AND P1.jt(j) = P2.jt(i')

the pair is considered to be a possible match.

Use of this additional contextual information will reduce the number of point pairs that need to be compared by the "BA" portion of the enhanced algorithm, PTM/EA, thus reducing the running time.

Furthermore, one may increase the mismatch tolerance because if junction types match, then one is willing to tolerate a less precise length match as the point pairs are more likely to represent the same features. As will be seen, increasing the mismatch tolerance to 0.15 results in approximately the same number of entries into the CCD matrix by allowing a more sloppy, while at the same time more

confident, match of point pairs. This might allow a map which does not very accurately depict "ground truth" to be successfully matched to an aerial photograph of the area.

Other (specific) enhancements will be discussed under the types of noise they are designed to reduce.

4.2. Effects of noise cn enhanced matching

4.2.1. Reducing Brownian motion noise effects

As can be seen in Figure 17a-d, the general enhancements described above yield a significant improvment in response. While PTM/BA suffered an 85% reduction in the concentration strengths clustered about CCD(0, 0) for one unit movement, PTM/EA suffered only a 36% reduction. In the case of two units' movement, PTM/BA produced no discernible clusters, PTM/EA yielded a scattered cluster centered about CCD(0, 0); this suggests an additional enhancement (not implemented) as described belcw. Four and eight units' movement produced no siginficant concentrations for either version.

If one expects Brcwnian mction of one/two units, a cluster detection template such as Figure 18 could be applied to detect the scattered clusters in the CCD matrix (see Rosenfeld and Kak [82]).

4.2.2. Reducing rotaticnal noise effects

Results for rotational ncise are similar to those for Brownian noise - see Figure 19a-f. In the case of a 5

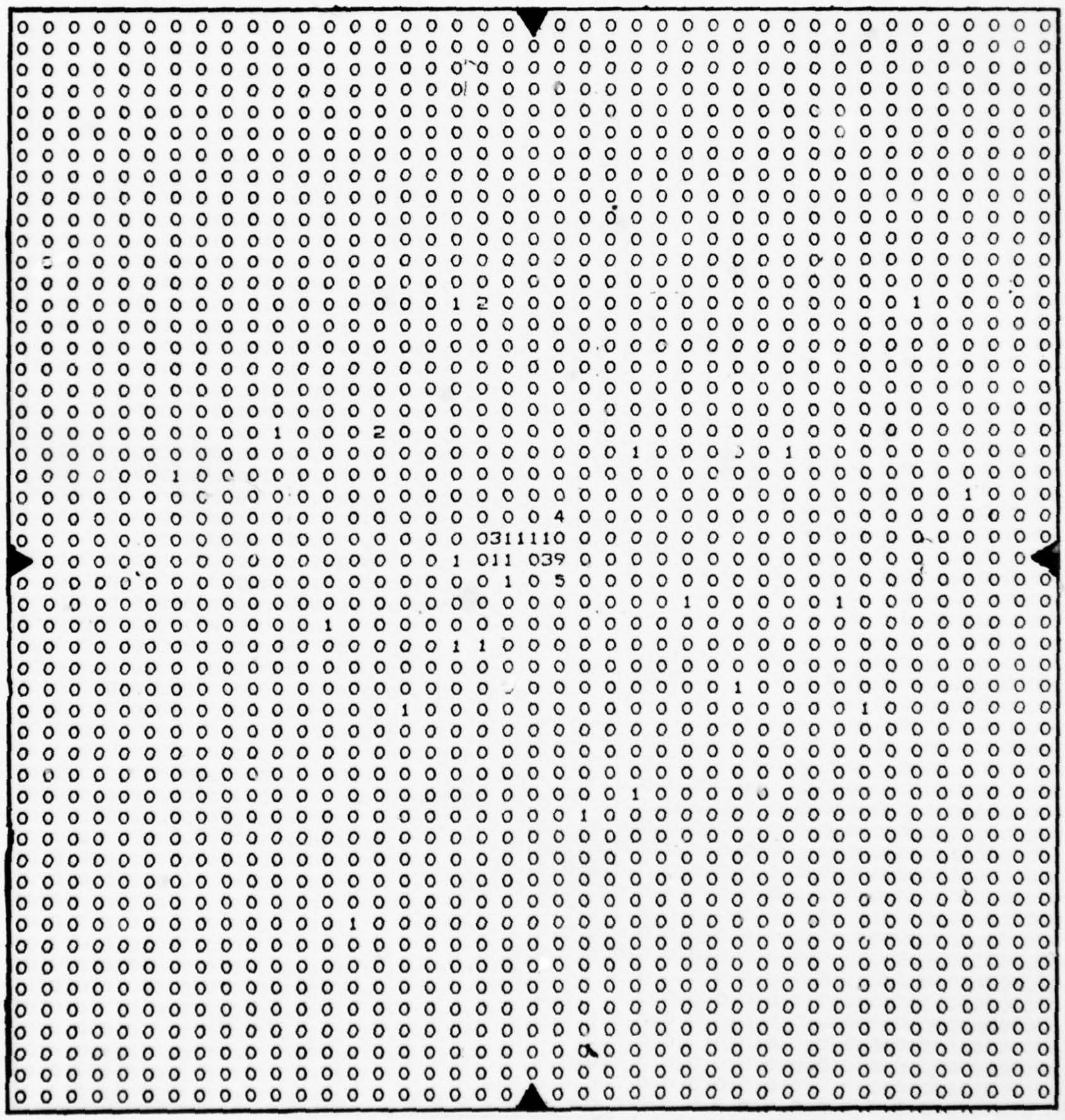

Figure 17a. MAP2 vs. MAP2.B1 with tolerance 0.15

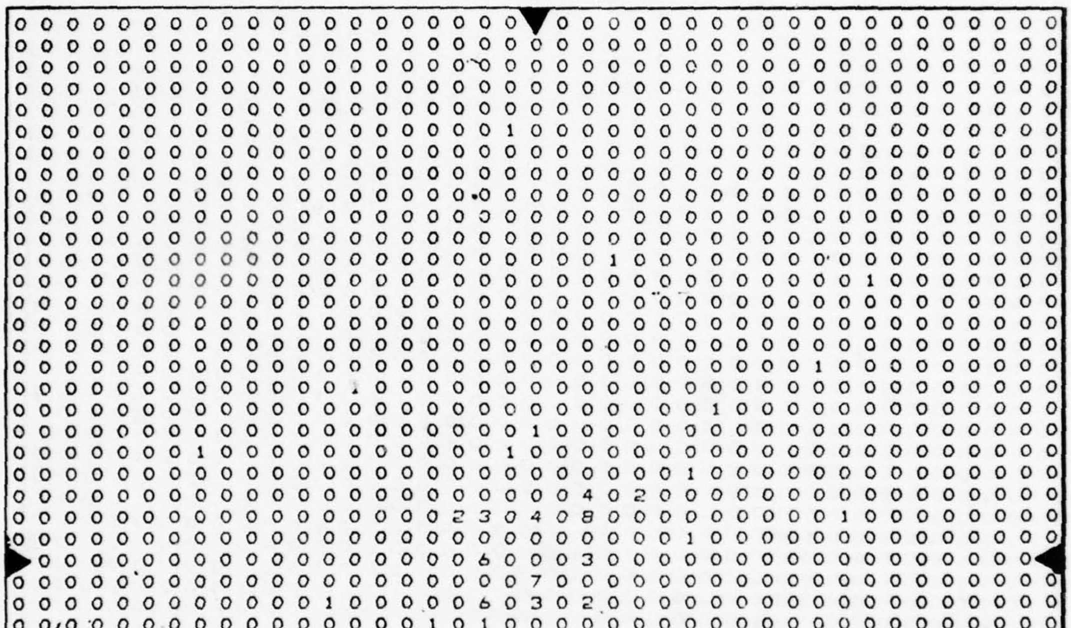

Figure 17b. MAP2 vs. MAP2.B2 with tolerance 0.15.

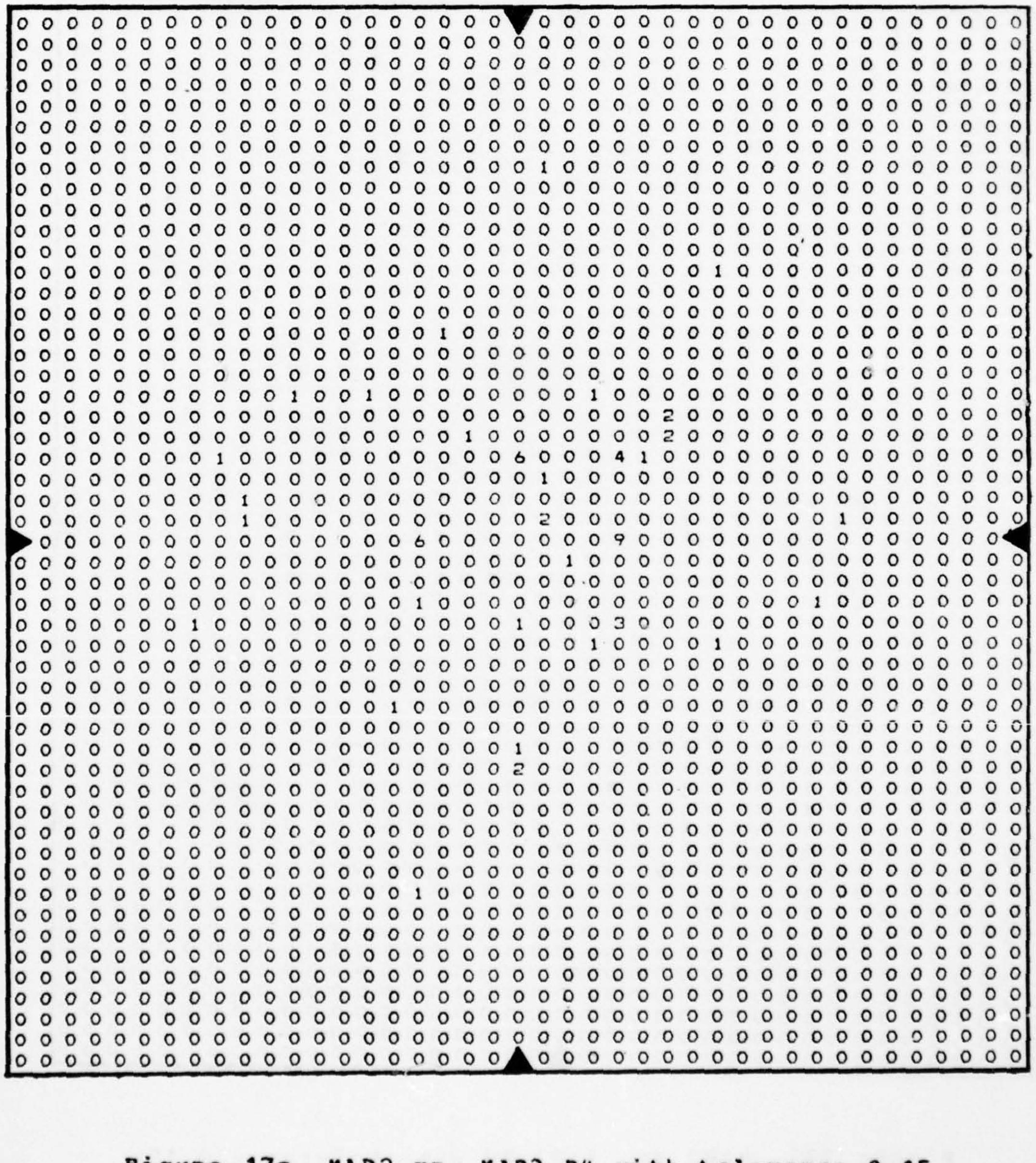

Figure 17c. MAP2 vs. MAP2.B4 with tolerance 0.15.

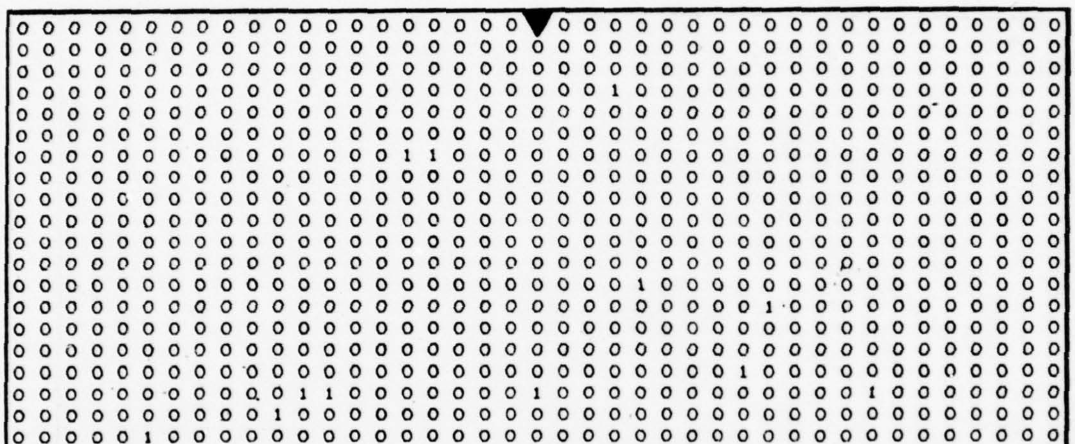

Figure 17d. MAP2 vs. MAP2.B8 with tolerance 0.15.

1	1	1	1	1
1	2	2	2	1
1	2	4	2	1
1	2	2	2	1
1	1	1	1	1

Figure 18. Cluster detection template.

degree rotation PTM/BA suffered an 84% reduction in concentration strengths whereas PTM/EA suffered only a 17% reduction. For 10 degrees of rotation no significant concentrations were produced by PTM/BA while PTM/EA yielded a scattered cluster similar to the one described above for Brownian movement of two units. Hence, cluster detection templates would prove useful here also.

As previously mentioned, if junction types match, two point pairs are likely to represent the same features. Given this assumption, one can determine, fairly accurately, the relative rotation of one sketch with respect to the other by means of a "rotational histogram".

The rotational histogram is computed as follows. If junction types match, then compute the difference in slopes of the imaginary line segments determined by the point pairs. Divide the difference by the radian equivalent of 5

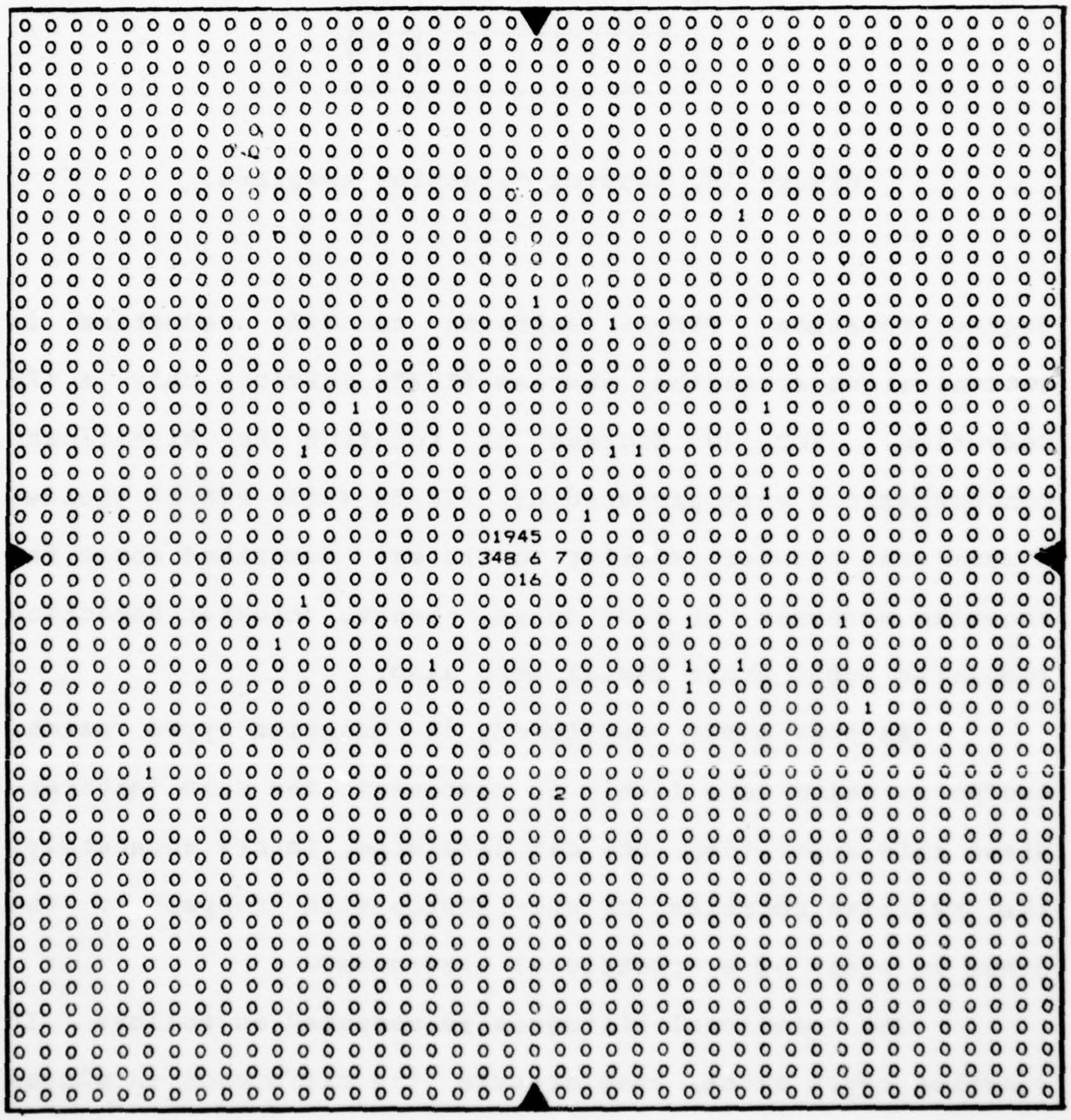

Figure 19a. MAP2 vs. MAP2.R5 with tolerance 0.15.

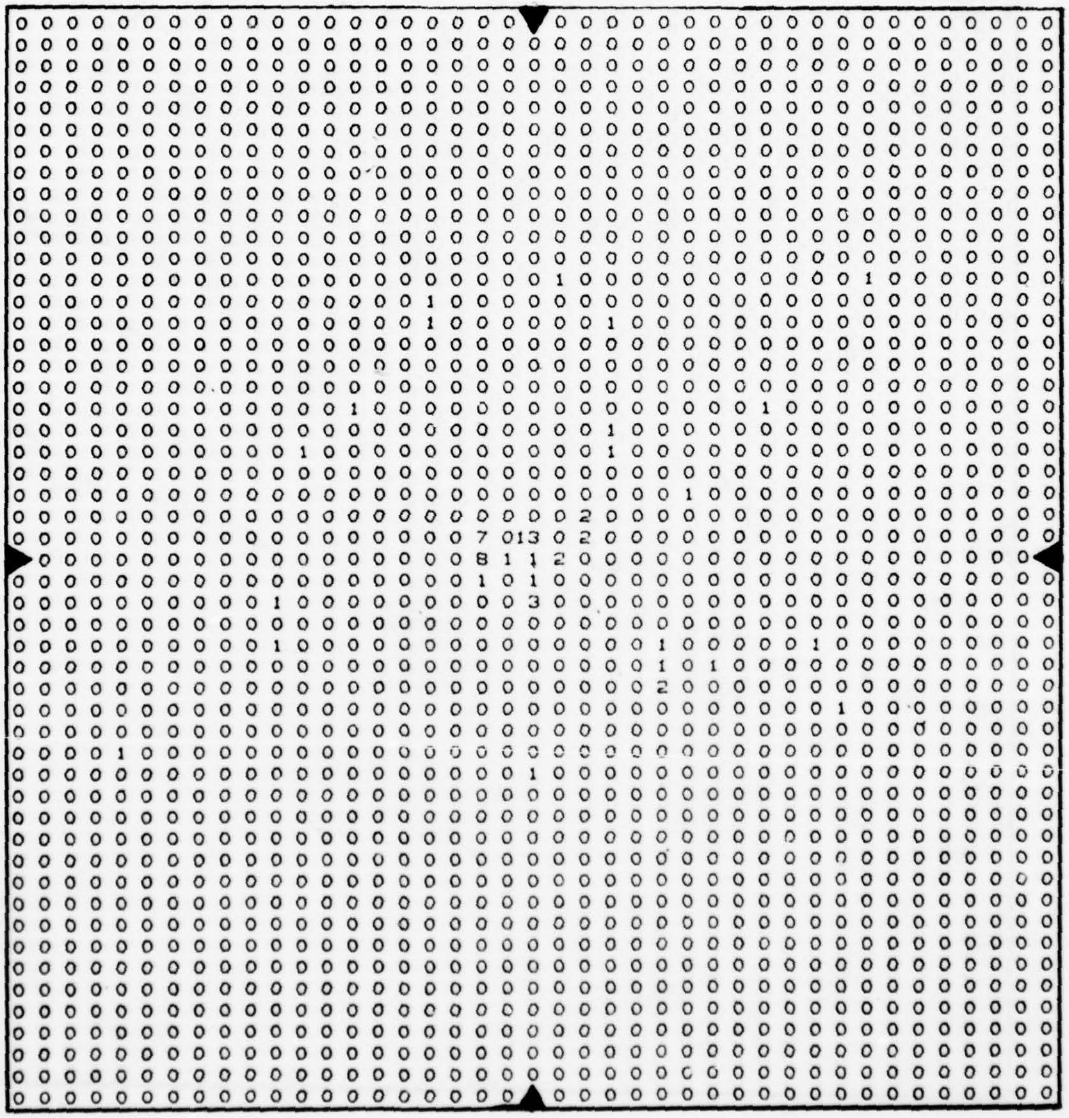

Figure 19b. MAP2 vs. MAP2.R10 with tolerance 0.15.

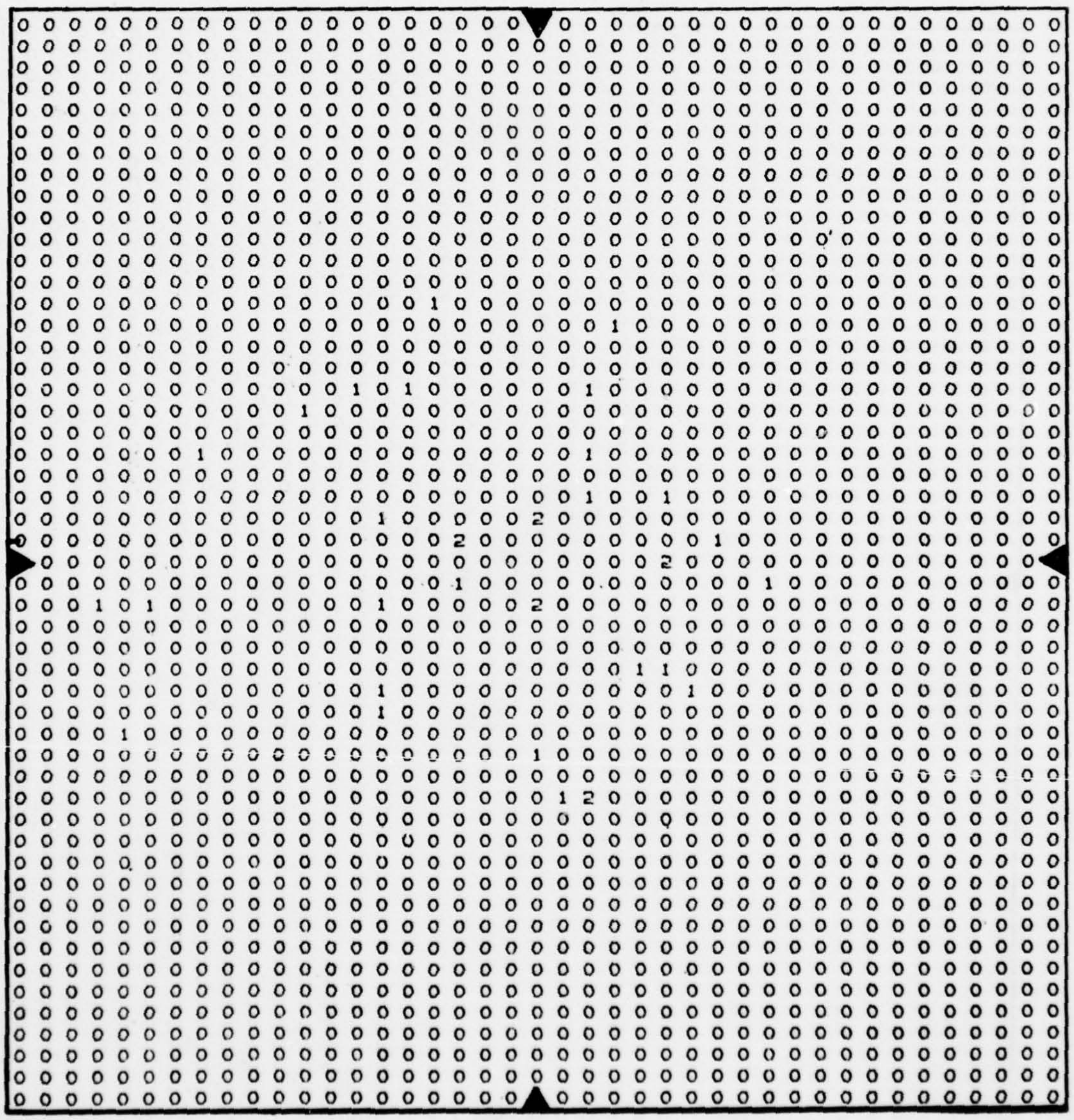

Figure 19c. MAP2 vs. MAP2.R15 with tolerance 0.15.

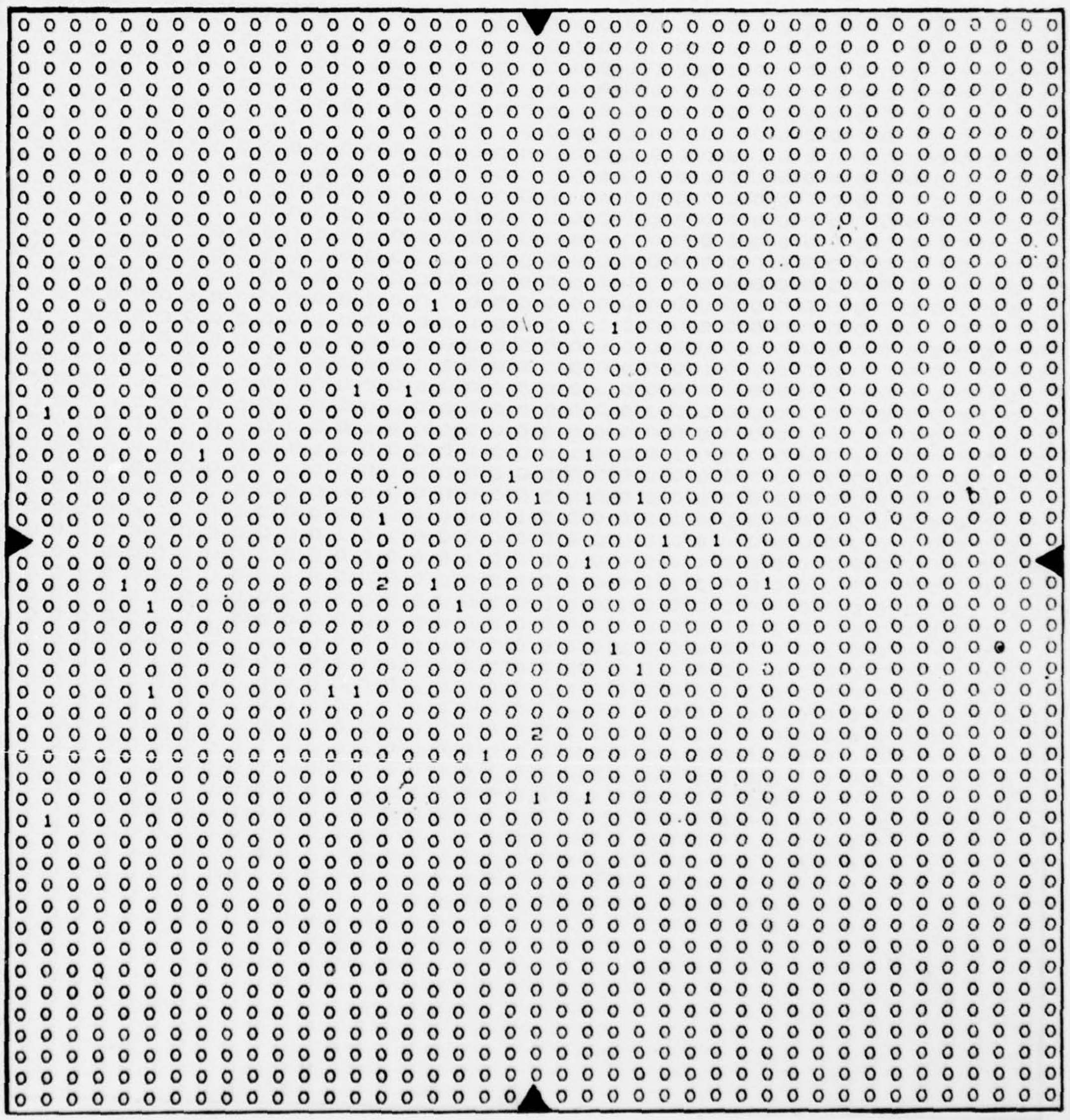

Figure 19d. MAP2 vs. MAP2.R20 with tolerance 0.15.

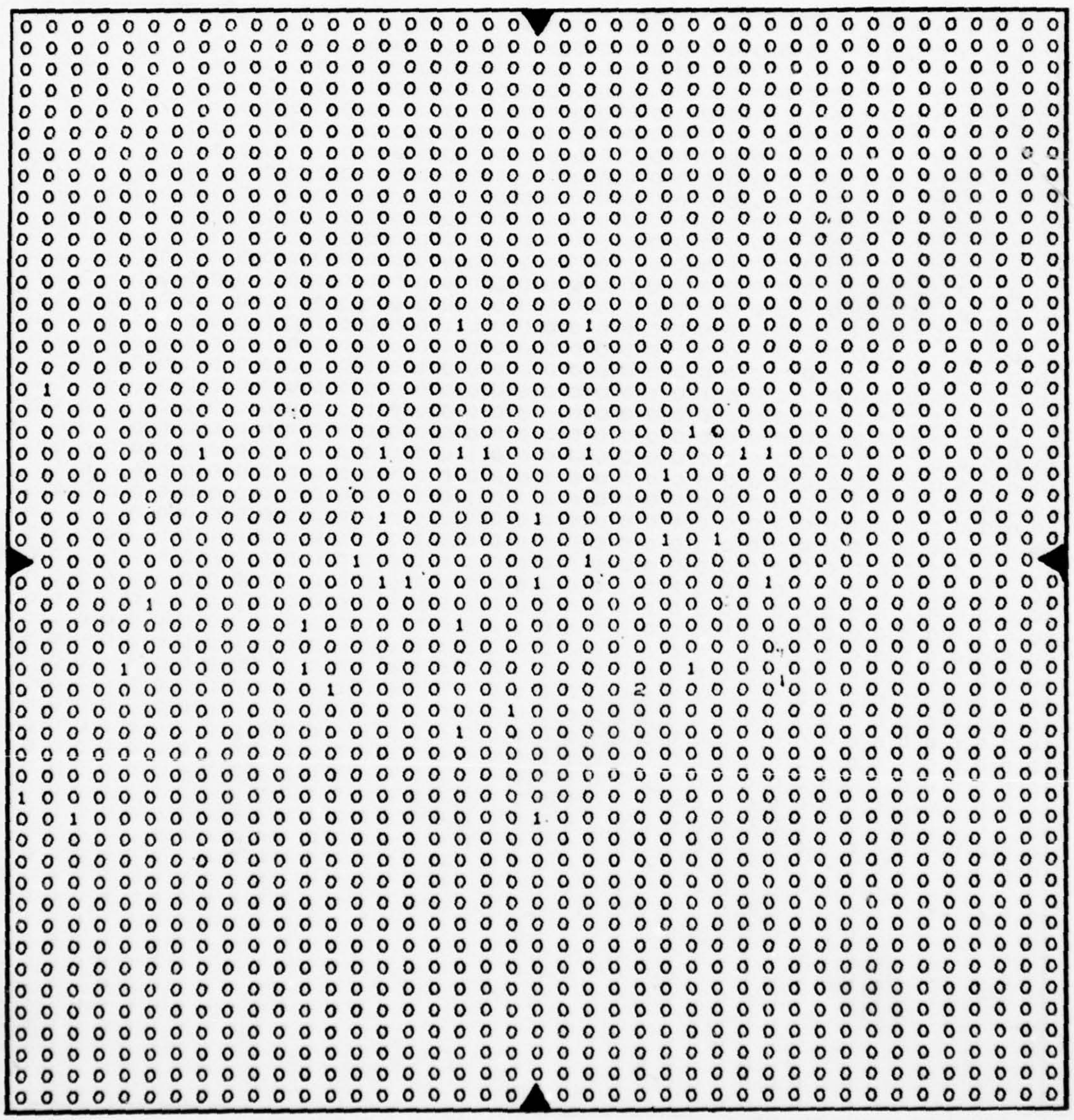

Figure 19e. MAP2 vs. MAP2.R25 with tolerance 0.15.

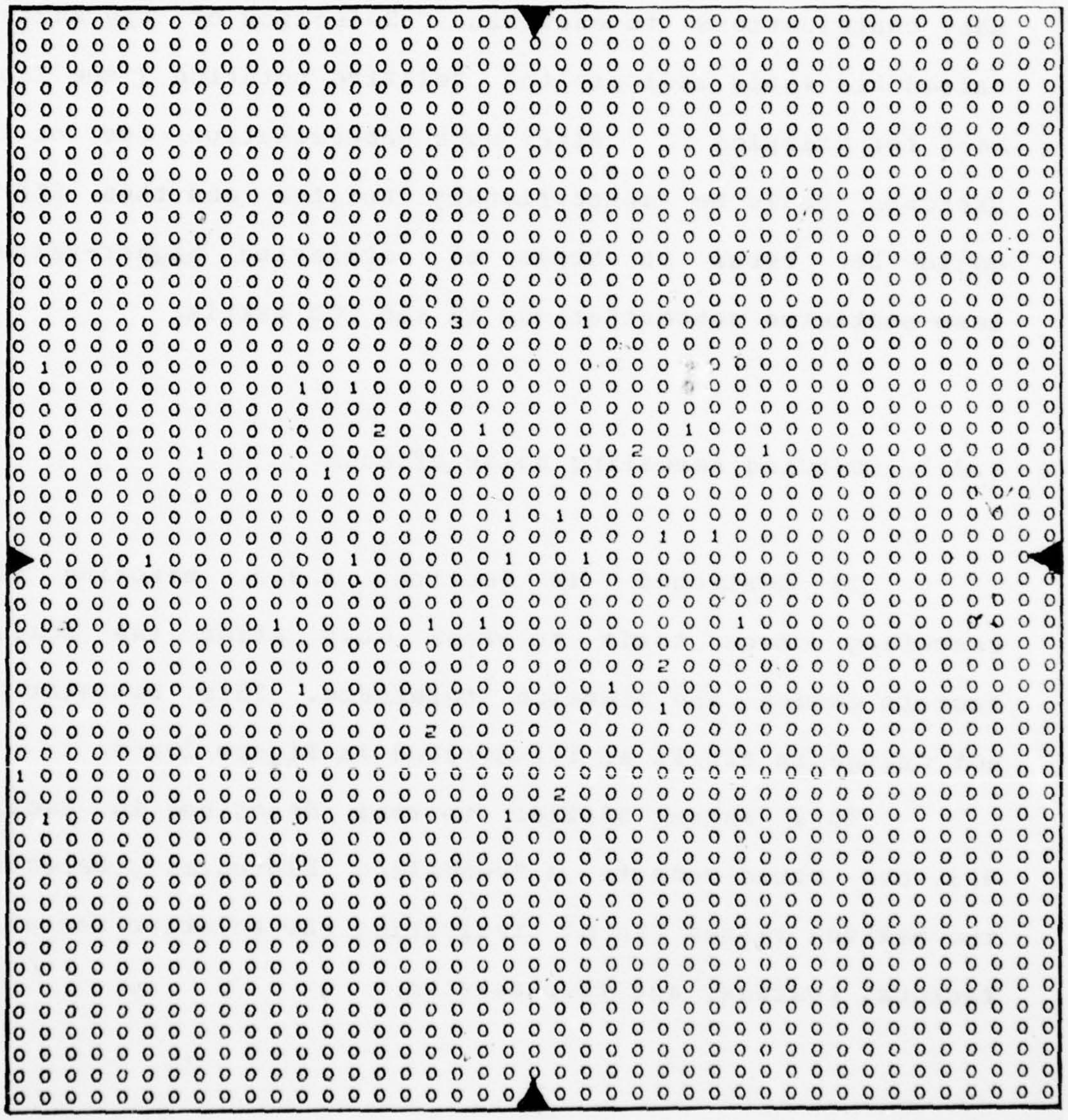

Figure 19f. MAP2 vs. MAP2.R30 with tolerance 0.15.

degrees. Use the quotient as a bin index and increment that bin's frequency count by one(1).

Using a bin width of 5 degrees was based on the ability of PTM/BA to produce significant concentrations in the case of 5 degrees of rotation as well as not wanting too many contributions to each bin. Selection of the maximum valued bin would indicate the relative rotation (see Table 6a-f for examples). After such determination, one of the sketches could be appropriately rotated and then PTM/EA could be rerun in hopes of achieving higher-valued, less-scattered concentrations in the CCD matrix.

4.2.3. Reducing rescaling noise effects

As mentioned in Section 3.3.3, matching for rescaling cases tends to break down after the scaling factors exceed the mismatch tolerance. This behavior did not change in PTM/EA as illustrated in Figure 20a-e.

In a manner similar to that described in Section 4.3, one could compute a "rescaling histogram", selecting the maximum valued bin as indicating the relative rescaling factors, rescale, and then rematch.

ROTATIONAL HISTOGRAM

Degree range	Frequency
-177 ~ -173	5
-172 ~ -168	1
-167 ~ -163	3
-162 ~ -158	0
-157 ~ -153	1
-152 ~ -148	4
-147 ~ -143	4
-142 ~ -138	4
-137 ~ -133	5
-132 ~ -128	8
-127 ~ -123	2
-122 ~ -118	6
-117 ~ -113	4
-112 ~ -108	2
-107 ~ -103	2
-102 ~ -98	3
-97 ~ -93	8
-92 ~ -88	10
-87 ~ -83	8
-82 ~ -78	8
-77 ~ -73	11
-72 ~ -68	14
-67 ~ -63	12
-62 ~ -58	9
-57 ~ -53	11
-52 ~ -48	11
-47 ~ -43	13
-42 ~ -38	19
-37 ~ -33	13
-32 ~ -28	17
-27 ~ -23	11
-22 ~ -18	15
-17 ~ -13	12
-12 ~ -8	9
-7 ~ -3	2
-2 ~ 2	42
3 ~ 7	111
8 ~ 12	25
13 ~ 17	16
18 ~ 22	9
23 ~ 27	10
28 ~ 32	17
33 ~ 37	15
38 ~ 42	12
43 ~ 47	10
48 ~ 52	13
53 ~ 57	15
58 ~ 62	11
63 ~ 67	8
68 ~ 72	8
73 ~ 77	10
78 ~ 82	9
83 ~ 87	7
88 ~ 92	7
93 ~ 97	12
98 ~ 102	5
103 ~ 107	5
108 ~ 112	5
113 ~ 117	3
118 ~ 122	8
123 ~ 127	5
128 ~ 132	3
133 ~ 137	5
138 ~ 142	1
143 ~ 147	2
148 ~ 152	6

Table 6a. Rotational histogram for rotation of 5 degrees.

ROTATIONAL HISTOGRAM

Degree range	Frequency
-177 ~ -173	5
-172 ~ -168	2
-167 ~ -163	3
-162 ~ -158	2
-157 ~ -153	0
-152 ~ -148	2
-147 ~ -143	6
-142 ~ -138	4
-137 ~ -133	6
-132 ~ -128	3
-127 ~ -123	7
-122 ~ -118	2
-117 ~ -113	5
-112 ~ -108	8
-107 ~ -103	1
-102 ~ -98	2
-97 ~ -93	10
-92 ~ -88	5
-87 ~ -83	9
-82 ~ -78	8
-77 ~ -73	6
-72 ~ -68	10
-67 ~ -63	11
-62 ~ -58	9
-57 ~ -53	8
-52 ~ -48	17
-47 ~ -43	11
-42 ~ -38	16
-37 ~ -33	12
-32 ~ -28	11
-27 ~ -23	17
-22 ~ -18	10
-17 ~ -13	14
-12 ~ -8	13
-7 ~ -3	0
-2 ~ 2	18
3 ~ 7	32
8 ~ 12	102
13 ~ 17	34
18 ~ 22	7
23 ~ 27	6
28 ~ 32	7
33 ~ 37	19
38 ~ 42	11
43 ~ 47	9
48 ~ 52	16
53 ~ 57	15
58 ~ 62	14
63 ~ 67	11
68 ~ 72	5
73 ~ 77	12
78 ~ 82	12
83 ~ 87	4
88 ~ 92	10
93 ~ 97	5
98 ~ 102	8
103 ~ 107	8
108 ~ 112	7
113 ~ 117	1
118 ~ 122	1
123 ~ 127	8
128 ~ 132	5
133 ~ 137	1
138 ~ 142	4
143 ~ 147	3
148 ~ 152	3

Table 6b. Rotational histogram for rotation of 10 degrees.

ROTATIONAL HISTOGRAM

Degree range	Frequency
-177 ~ -173	0
-172 ~ -168	8
-167 ~ -163	4
-162 ~ -158	2
-157 ~ -153	2
-152 ~ -148	2
-147 ~ -143	1
-142 ~ -138	5
-137 ~ -133	4
-132 ~ -128	5
-127 ~ -123	6
-122 ~ -118	5
-117 ~ -113	3
-112 ~ -108	7
-107 ~ -103	4
-102 ~ -98	8
-97 ~ -93	7
-92 ~ -88	7
-87 ~ -83	5
-82 ~ -78	5
-77 ~ -73	12
-72 ~ -68	9
-67 ~ -63	9
-62 ~ -58	12
-57 ~ -53	11
-52 ~ -48	11
-47 ~ -43	12
-42 ~ -38	18
-37 ~ -33	10
-32 ~ -28	22
-27 ~ -23	14
-22 ~ -18	10
-17 ~ -13	16
-12 ~ -8	15
-7 ~ -3	2
-2 ~ 2	11
3 ~ 7	9
8 ~ 12	44
13 ~ 17	101
18 ~ 22	24
23 ~ 27	12
28 ~ 32	7
33 ~ 37	16
38 ~ 42	9
43 ~ 47	10
48 ~ 52	13
53 ~ 57	11
58 ~ 62	14
63 ~ 67	15
68 ~ 72	7
73 ~ 77	7
78 ~ 82	12
83 ~ 87	11
88 ~ 92	8
93 ~ 97	4
98 ~ 102	9
103 ~ 107	6
108 ~ 112	5
113 ~ 117	4
118 ~ 122	6
123 ~ 127	5
128 ~ 132	5
133 ~ 137	2
138 ~ 142	2
143 ~ 147	3
148 ~ 152	3

Table 6c. Rotational histogram for rotation of 15 degrees.

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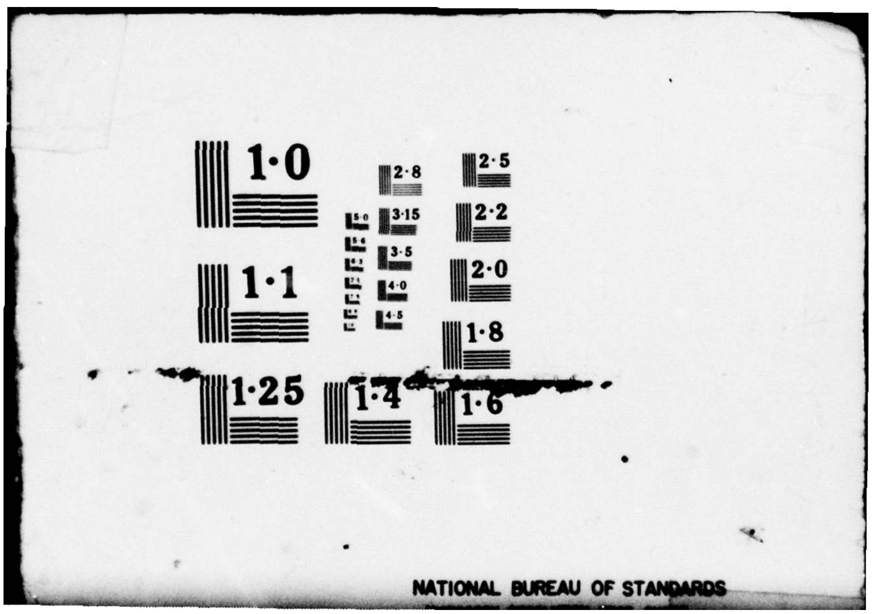
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2·8
2·5
3·15
2·2
3·5
1·1
2·0
4·0
4·5
1·8
1·25
1·4
1·6
NATIONAL BUREAU OF STANDARDS

ROTATIONAL HISTOGRAM

Degree range			Frequency
-177	~	-173	1
-172	~	-168	1
-167	~	-163	15
-162	~	-158	2
-157	~	-153	3
-152	~	-148	2
-147	~	-143	1
-142	~	-138	4
-137	~	-133	4
-132	~	-128	5
-127	~	-123	6
-122	~	-118	3
-117	~	-113	6
-112	~	-108	3
-107	~	-103	5
-102	~	-98	5
-97	~	-93	3
-92	~	-88	5
-87	~	-83	7
-82	~	-78	8
-77	~	-73	8
-72	~	-68	12
-67	~	-63	8
-62	~	-58	9
-57	~	-53	17
-52	~	-48	7
-47	~	-43	7
-42	~	-38	20
-37	~	-33	13
-32	~	-28	15
-27	~	-23	16
-22	~	-18	17
-17	~	-13	15
-12	~	-8	12
-7	~	-3	2
-2	~	2	15
3	~	7	10
8	~	12	13
13	~	17	29
18	~	22	93
23	~	27	35
28	~	32	15
33	~	37	7
38	~	42	14
43	~	47	11
48	~	52	8
53	~	57	15
58	~	62	11
63	~	67	12
68	~	72	13
73	~	77	12
78	~	82	5
83	~	87	12
88	~	92	7
93	~	97	6
98	~	102	8
103	~	107	6
108	~	112	6
113	~	117	4
118	~	122	4
123	~	127	6
128	~	132	1
133	~	137	4
138	~	142	3
143	~	147	2
148	~	152	3

Table 6d. Rotational histogram for rotation of 20 degrees.

ROTATIONAL HISTOGRAM

Degree range	Frequency
-177 ~ -173	0
-172 ~ -168	0
-167 ~ -163	2
-162 ~ -158	4
-157 ~ -153	15
-152 ~ -148	5
-147 ~ -143	4
-142 ~ -138	2
-137 ~ -133	4
-132 ~ -128	2
-127 ~ -123	8
-122 ~ -118	4
-117 ~ -113	6
-112 ~ -108	6
-107 ~ -103	3
-102 ~ -98	4
-97 ~ -93	9
-92 ~ -88	4
-87 ~ -83	4
-82 ~ -78	2
-77 ~ -73	11
-72 ~ -68	7
-67 ~ -63	13
-62 ~ -58	7
-57 ~ -53	7
-52 ~ -48	7
-47 ~ -43	12
-42 ~ -38	15
-37 ~ -33	11
-32 ~ -28	13
-27 ~ -23	16
-22 ~ -18	15
-17 ~ -13	14
-12 ~ -8	20
-7 ~ -3	3
-2 ~ 2	15
3 ~ 7	16
8 ~ 12	10
13 ~ 17	9
18 ~ 22	13
23 ~ 27	40
28 ~ 32	98
33 ~ 37	26
38 ~ 42	12
43 ~ 47	4
48 ~ 52	11
53 ~ 57	13
58 ~ 62	9
63 ~ 67	16
68 ~ 72	12
73 ~ 77	14
78 ~ 82	10
83 ~ 87	9
88 ~ 92	5
93 ~ 97	11
98 ~ 102	10
103 ~ 107	6
108 ~ 112	5
113 ~ 117	4
118 ~ 122	6
123 ~ 127	6
128 ~ 132	4
133 ~ 137	4
138 ~ 142	2
143 ~ 147	6
148 ~ 152	2

Table 6e. Rotational histogram for rotation of 30 degrees.

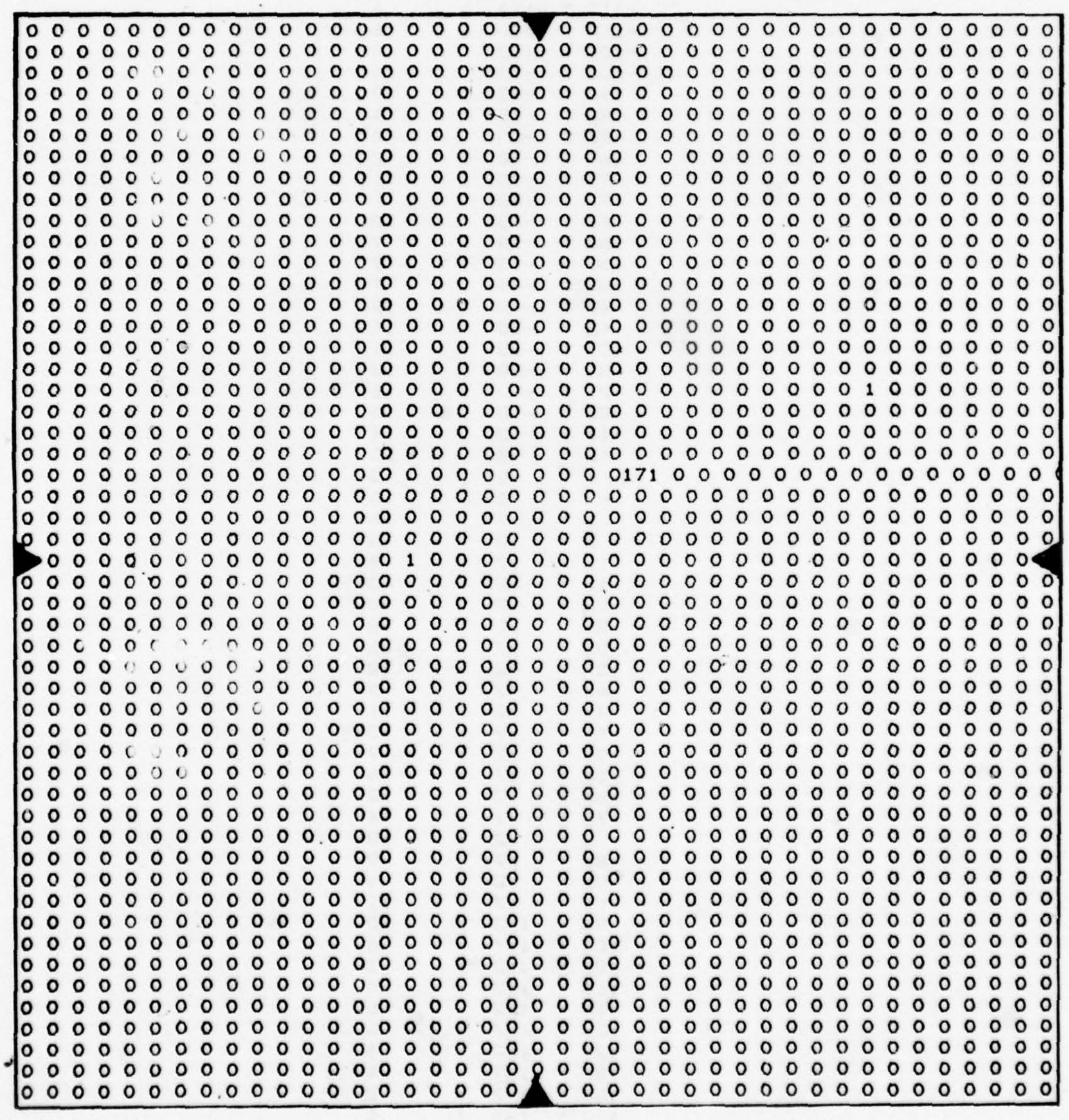

Figure 20a. MAP2 vs. MAP2.S01 with tolerance 0.15.

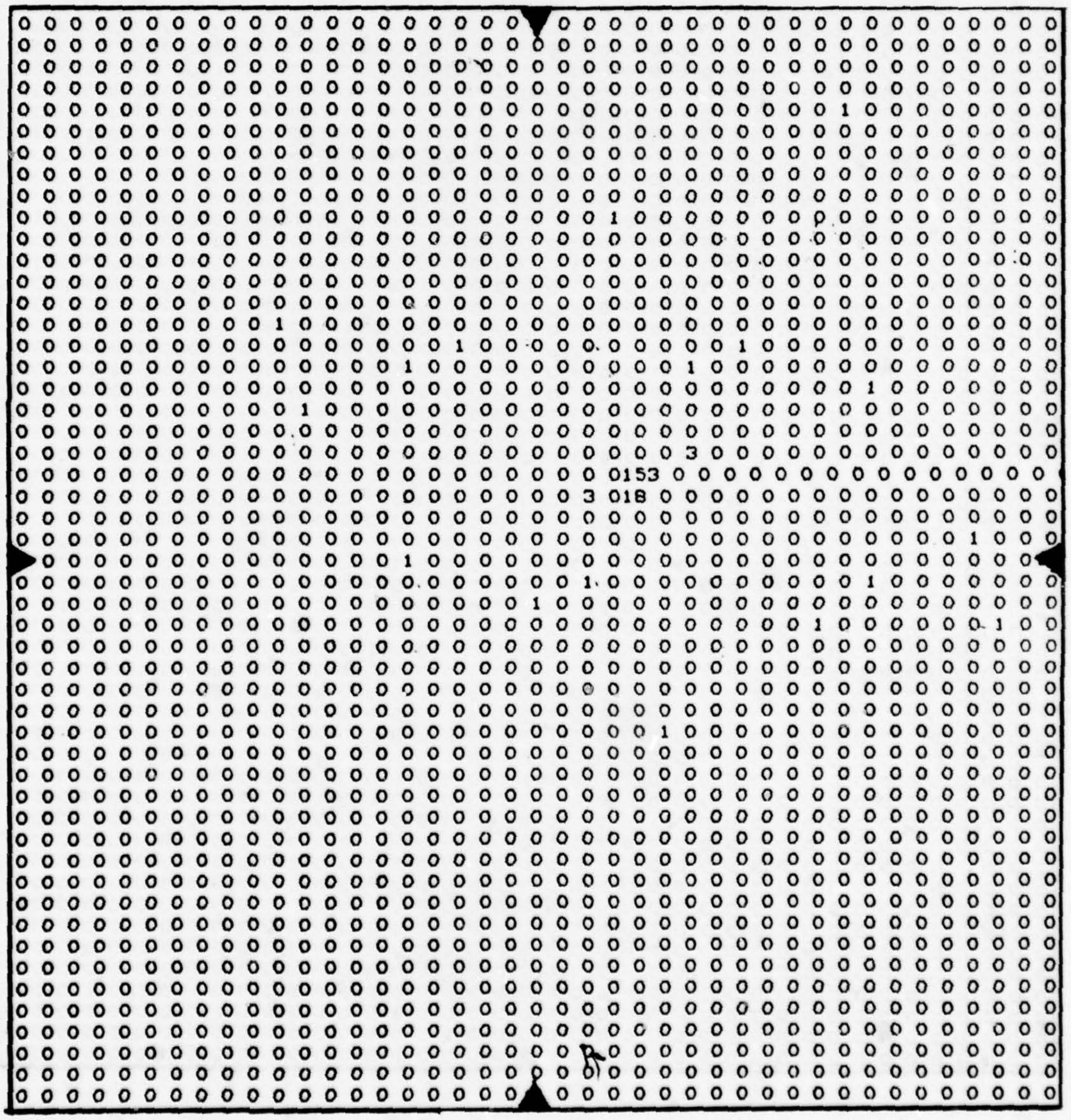

Figure 20b. MAP2 vs. MAP2.S02 with tolerance 0.15.

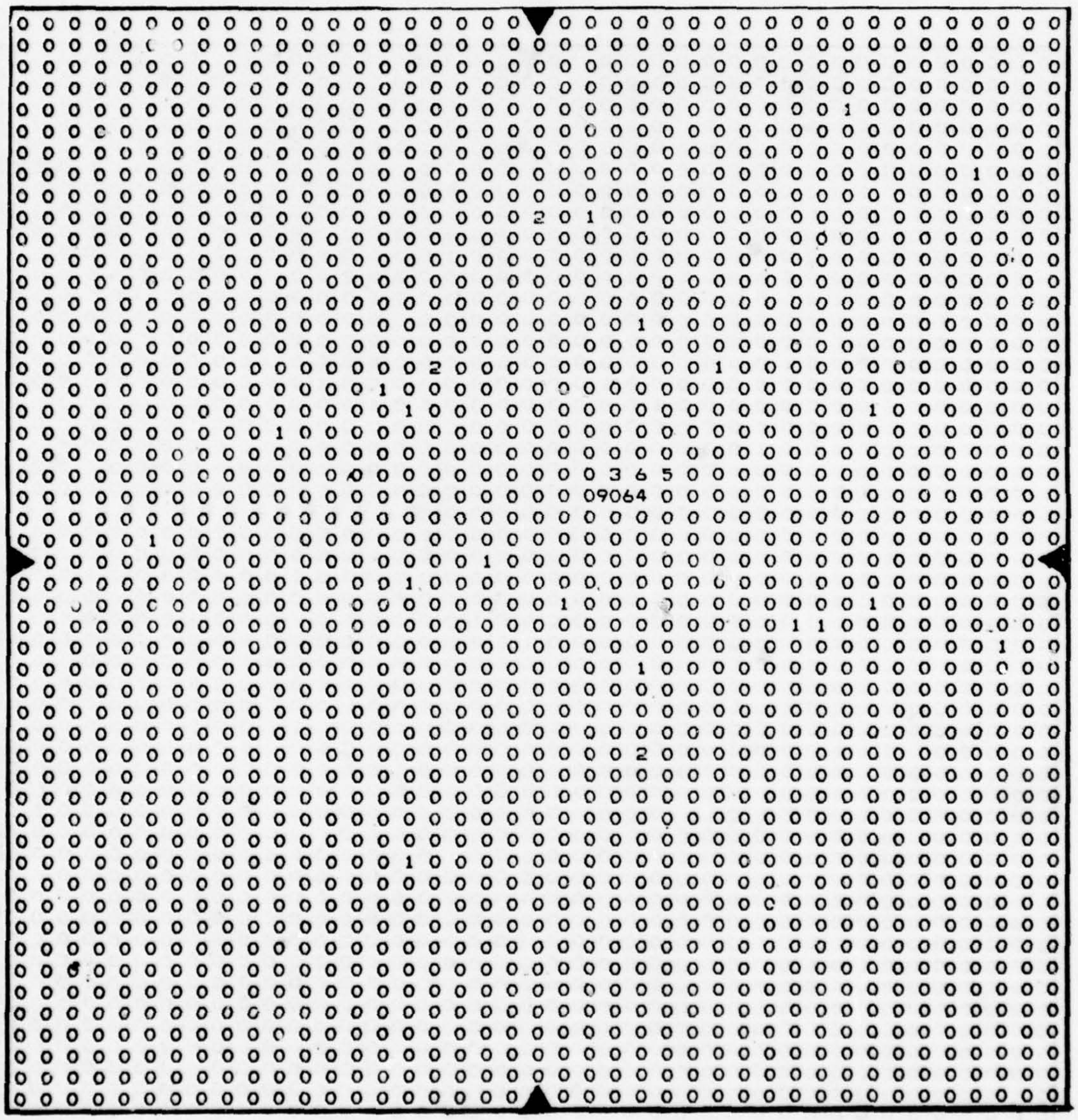

Figure 20c. MAP2 vs. MAP2.S05 with tolerance 0.15.

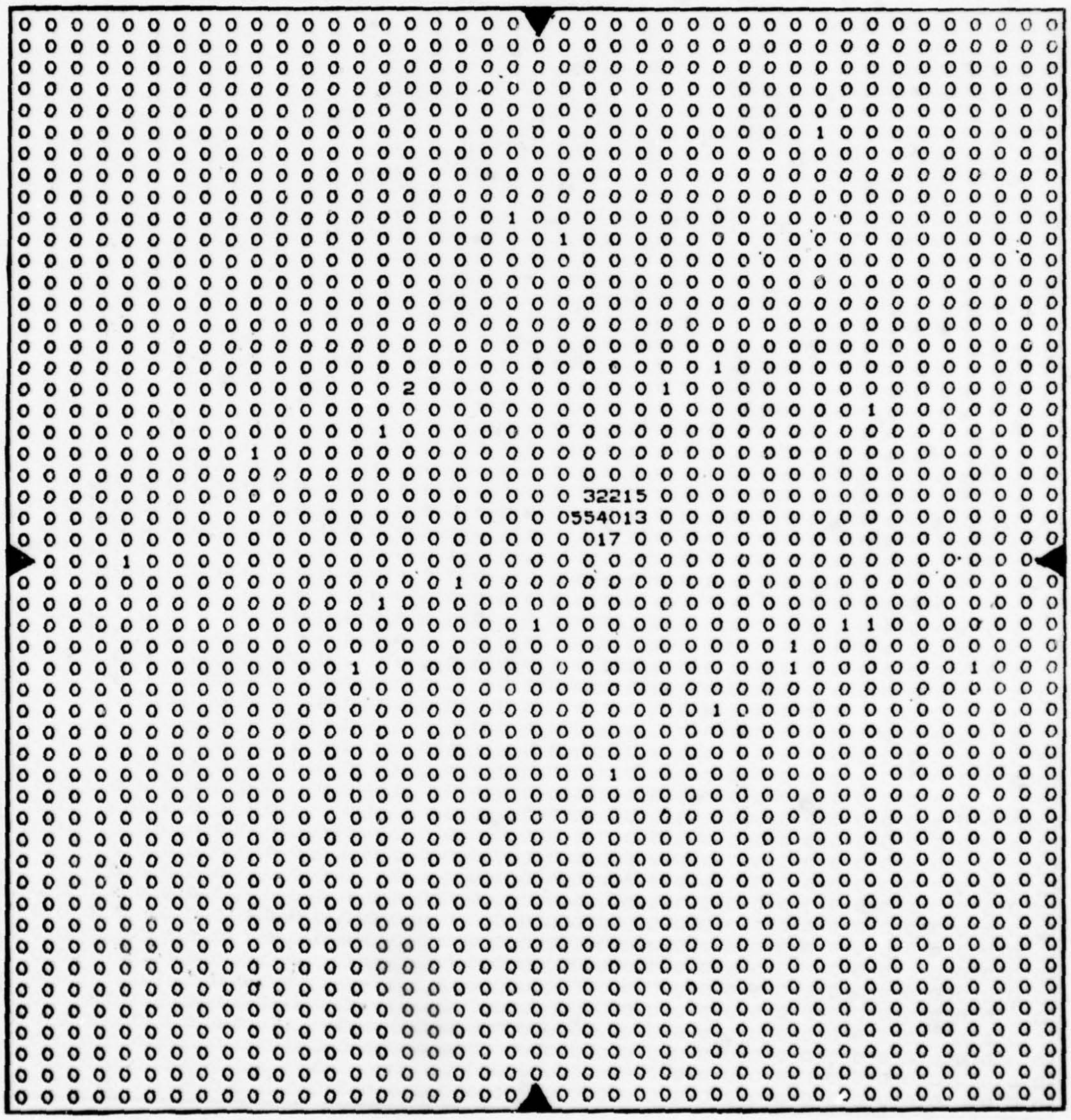

Figure 20d. MAP2 vs. MAP2.S10 with tolerance 0.15.

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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ▲ 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

Figure 20e. MAP2 vs. MAP2.S15 with tolerance 0.15.

CHAPTER 5

CONCLUSIONS

This chapter summarizes the results reported in Chapters 2-4 and suggests areas for additional research.

5.1. Recommendations

While the relative rotation between sketches can be determined, a method for determining the point about which rotation has occurred needs to be developed. The author, for purposes of this research, chose to assume rotation would have been about the eyeball estimate of the point closest to the centroid.

Both versions of the algorithm, PTM/BA and PTM/EA, are order(N**4). An approach which might be taken could be a kind of state space search. If the algorithm were to monitor the CCD matrix and it noticed a build-up of a significant (cluster of) concentration, then the "path" defined by that concentration could be *followed;* that is, only those pairs that would contribute to the same concentration would be matched. If a "sufficient" proportion of the maximum number of possible matches occurred, then the algorithm would terminate with a successful matching. If such a heuristic, state space search were applied to two matching sketches, actual running time should be considerably less than order N**4.

Additionally, the sketch data-point files could be sorted on junction type values from most to least distinctive/complex. After sorting, points with the same, most distinctive junction types would be matched. If the monitor noticed a significant concentration, the path

defined by that concentration could be followed as above. Otherwise, points with nearly the same junction types could be matched; then similar junction types if no matches discovered and so forth until in the case of non-matching sketches all points would have been matched.

One last refinement could function as follows. Define some minimal concentration threshold value. If this threshold were not exceeded after some appropriate proportion of points had been matched, then the algorithm would terminate with the indication that the sketches did not match.

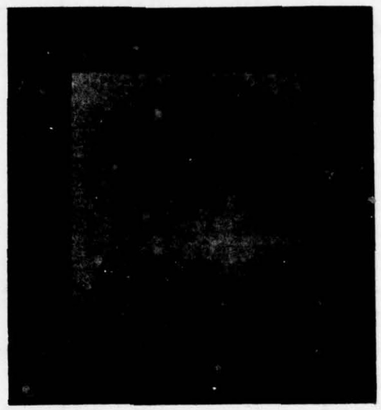
5.2. Summary

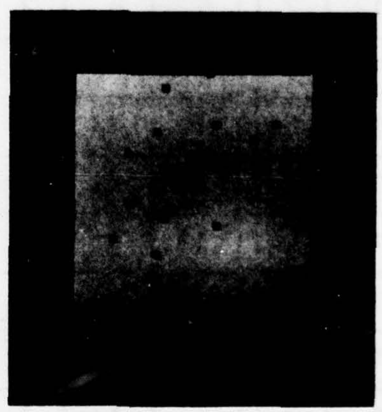
The goal of this thesis was to build a foundation for CVL's proposed map-guided segmentation system. Chapter 2 defined a simple, brute force sketch matching algorithm based on the relative positions of the (feature) points. A simple example illustrated the methodology.

Chapter 3 described how a suitable mismatch tolerance was selected and dealt with the effects of varying amounts of various types of noise (Brownian motion, rotation, rescaling, and random point replacement). Presented in Chapter 4 were various enhancements/suggestions to reduce the running time and the effects of noise. Addition of junction type label checking reduced the number of pairs that had to be matched "in full" and allowed a larger mismatch tolerance. Methods of determining the relative rotation and scale between sketches were presented.

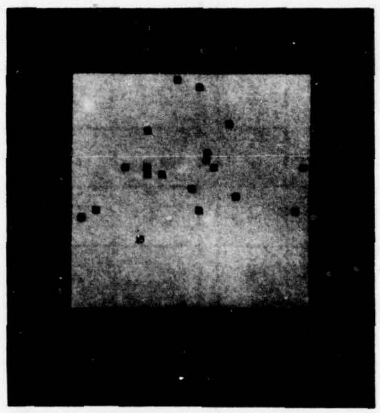
JUNCTION TYPE	LABEL
L	0
ARROW	1
T	2
FORK	3
X	4
4 LINES (NOT X)	5
5 OR MORE LINES	6

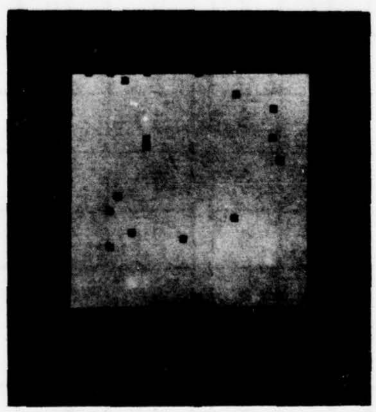
MAP2B1			MAP2B2		
X	Y	JT	X	Y	JT
17	31	2	18	32	2
9	28	3	12	30	3
21	19	5	20	18	5
14	26	5	11	24	5
24	25	4	27	25	4
8	22	4	7	21	4
19	22	4	19	25	4
23	20	5	24	23	5
13	19	2	12	16	2
28	18	5	25	19	5
15	19	6	14	16	6
4	15	2	7	14	2
13	16	3	12	13	3
18	14	5	16	17	5
10	13	4	12	12	4
27	13	4	28	13	4
8	10	4	5	9	4
16	9	2	19	11	2
13	6	3	11	7	3
-99	-99	0	-99	-99	0



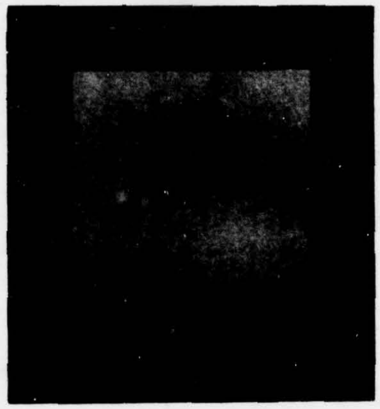


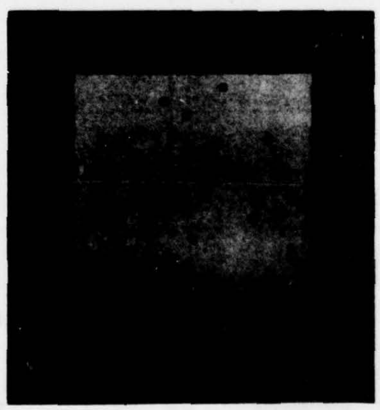
MAP2B4			MAP2B8		
X	Y	JT	X	Y	JT
14	31	2	10	32	2
10	24	3	2	32	3
16	16	5	28	20	5
17	30	5	5	32	5
21	25	4	17	32	4
7	19	4	7	31	4
19	19	4	27	23	4
18	21	5	22	29	5
18	20	2	22	12	2
31	19	5	27	27	5
12	18	6	8	10	6
1	12	2	5	8	2
10	19	3	6	15	3
22	15	5	10	23	5
10	18	4	10	22	4
30	13	4	32	5	4
3	13	4	15	9	4
17	13	2	17	1	2
9	9	3	5	13	3
-99	-99	0	-99	-99	0





MAP2R5			MAP2R10		
X	Y	JT	X	Y	JT
19	30	2	20	30	2
11	28	3	12	28	3
20	19	5	20	19	5
14	26	5	15	26	5
25	24	4	26	23	4
8	23	4	9	24	4
19	22	4	19	22	4
22	20	5	22	19	5
15	20	2	15	20	2
27	18	5	27	18	5
16	18	6	16	18	6
5	17	2	5	18	2
14	16	3	14	16	3
17	15	5	17	15	5
10	15	4	10	16	4
25	13	4	24	12	4
7	10	4	6	11	4
16	9	2	16	9	2
12	6	3	11	6	3
-99	-99	0	-99	-99	0





MAP2R15			MAP2R20		
X	Y	JT	X	Y	JT
21	30	2	22	29	2
13	29	3	14	29	3
20	18	5	20	18	5
16	26	5	16	26	5
26	22	4	26	21	4
9	25	4	10	25	4
20	22	4	20	21	4
22	19	5	22	18	5
15	20	2	15	20	2
26	17	5	26	16	5
16	18	6	16	18	6
5	18	2	5	19	2
14	16	3	14	16	3
17	15	5	16	15	5
10	16	4	9	17	4
24	11	4	23	10	4
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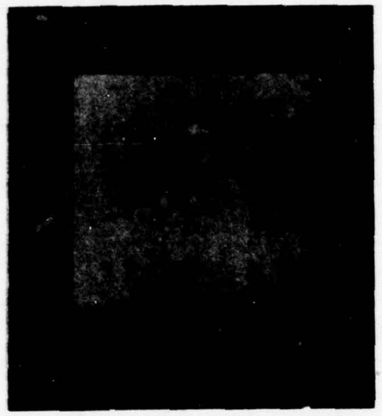
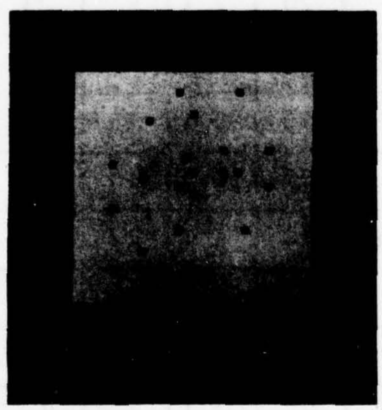
-99	-99	0	-99	-99	0





MAP2R25			MAP2R30		
X	Y	JT	X	Y	JT
23	28	2	24	28	2
15	29	3	16	29	3
20	18	5	20	18	5
16	26	5	17	26	5
27	20	4	27	19	4
10	26	4	11	26	4
20	21	4	21	20	4
22	18	5	22	18	5
16	20	2	16	20	2
26	15	5	26	14	5
16	18	6	16	18	6
6	20	2	6	21	2
13	17	3	13	17	3
16	15	5	16	15	5
9	17	4	9	18	4
22	10	4	22	9	4
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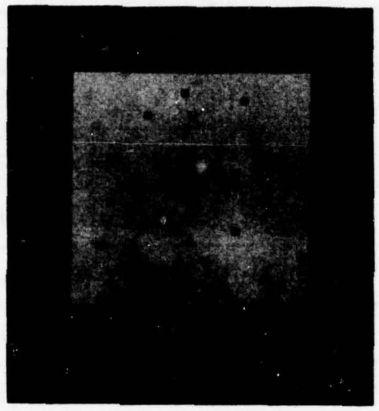
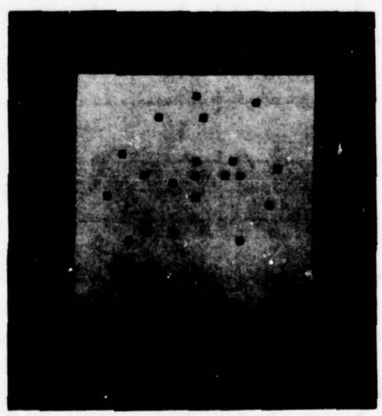
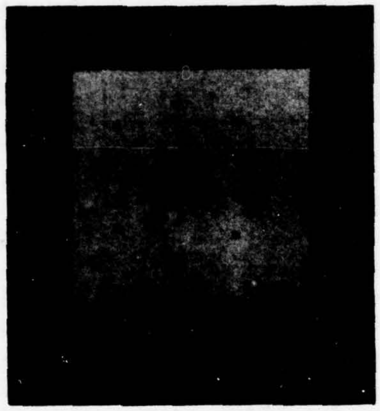
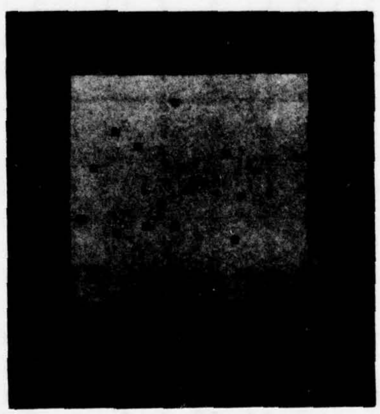
8	8	3	7	9	3
-99	-99	0	-99	-99	0



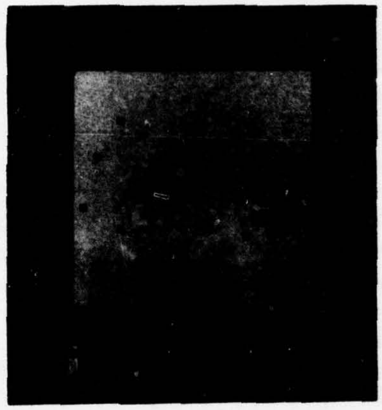


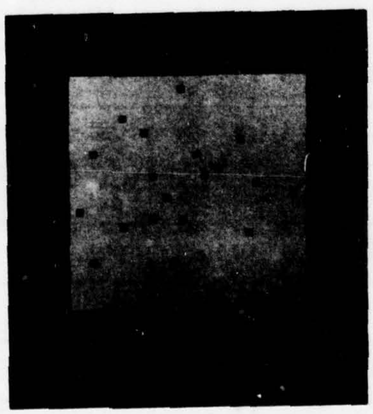
MAP2S01			MAP2S02		
X	Y	JT	X	Y	JT
14	27	2	14	28	2
6	24	3	6	24	3
16	16	5	16	16	5
9	22	5	9	22	5
21	21	4	21	21	4
3	19	4	3	19	4
15	19	4	15	19	4
18	17	5	18	17	5
10	16	2	10	16	2
23	15	5	23	15	5
12	14	6	12	14	6
1	12	2	1	12	2
10	11	3	10	11	3
14	11	5	14	11	5
6	10	4	6	10	4
22	9	4	22	9	4
3	5	4	3	5	4
13	5	2	13	5	2
9	1	3	9	1	3
-99	-99	0	-99	-99	0



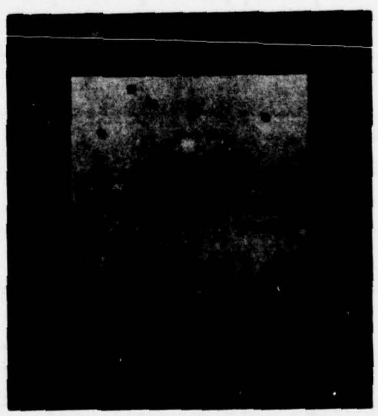


MAP2S05			MAP2S10		
X	Y	JT	X	Y	JT
15	28	2	15	30	2
6	25	3	7	26	3
17	17	5	18	18	5
9	23	5	10	24	5
22	22	4	23	23	4
3	20	4	3	21	4
16	20	4	17	21	4
19	18	5	20	19	5
10	17	2	11	18	2
24	16	5	25	17	5
13	15	6	13	15	6
1	13	2	1	13	2
10	12	3	11	12	3
15	12	5	15	12	5
6	10	4	7	11	4
23	9	4	24	10	4
3	5	4	3	6	4
14	5	2	14	6	2
9	1	3	10	1	3
-99	-99	0	-99	-99	0





MAP2S15			MAP2S20		
X	Y	JT	X	Y	JT
17	32	2	18	34	2
7	29	3	8	30	3
19	19	5	20	20	5
11	26	5	11	28	5
25	25	4	26	26	4
4	23	4	4	24	4
18	23	4	19	24	4
22	20	5	23	21	5
12	19	2	13	20	2
28	18	5	29	19	5
14	17	6	15	18	6
1	14	2	1	15	2
12	13	3	13	14	3
17	13	5	18	14	5
7	12	4	8	13	4
26	11	4	28	11	4
4	6	4	4	6	4
16	6	2	16	6	2
11	1	3	11	1	3
-99	-99	0	-99	-99	0



MAP2AD1			MAP2AD2		
X	Y	JT	X	Y	JT
18	31	2	18	31	2
10	28	3	10	28	3
20	20	5	13	26	5
13	26	5	25	25	4
25	25	4	7	23	4
7	23	4	19	23	4
19	23	4	22	21	5
22	21	5	14	20	2
14	20	2	27	19	5
27	19	5	5	16	2
16	16	6	14	15	3
14	15	3	18	15	5
18	15	5	10	14	4
10	14	4	26	13	4
26	13	4	7	9	4
7	9	4	17	9	2
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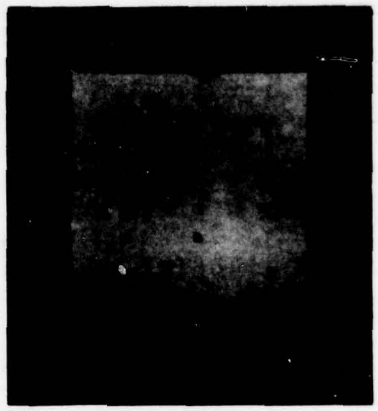

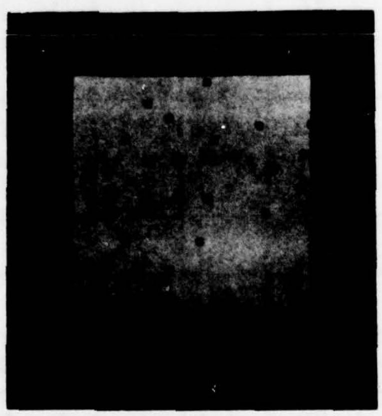

MAP2AD4			MAP2AD8		
X	Y	JT	X	Y	JT
18	31	2	18	31	2
10	28	3	10	28	3
20	20	5	20	20	5
13	26	5	13	26	5
25	25	4	25	25	4
7	23	4	7	23	4
19	23	4	19	23	4
22	21	5	22	21	5
14	20	2	14	20	2
27	19	5	27	19	5
16	18	6	16	18	6
5	16	2	24	14	2
14	15	3	31	4	3
18	15	5	19	5	5
10	14	4	15	17	4
27	2	4	27	24	4
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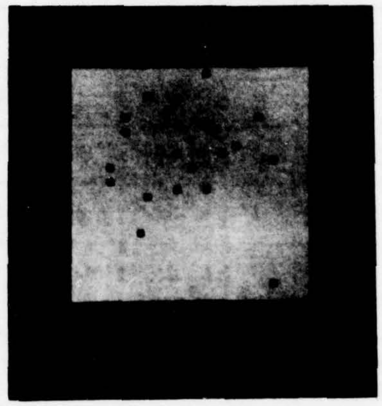
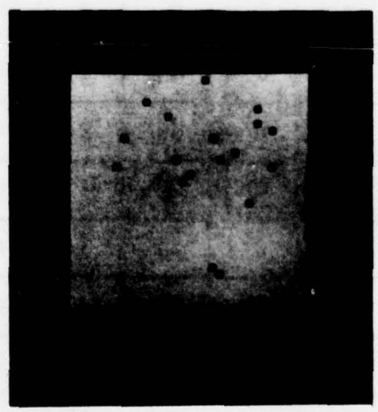
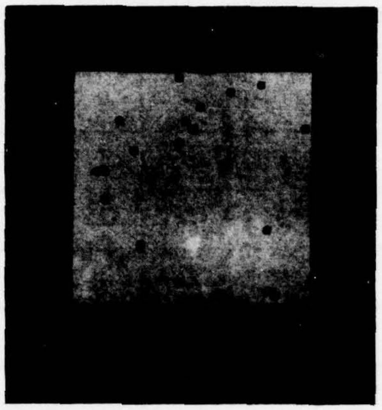
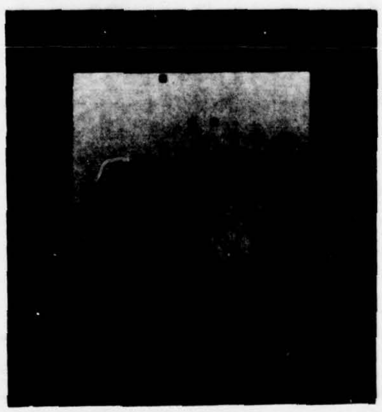




RANDPTS1			RANDPTS2		
X	Y	JT	X	Y	JT
20	19	0	24	5	0
32	3	0	19	25	0
18	32	0	27	20	0
25	30	0	3	3	0
21	29	0	16	24	0
14	22	0	14	0	0
15	25	0	11	0	0
27	1	0	14	8	0
4	18	0	15	13	0
9	8	0	14	1	0
6	25	0	14	13	0
20	1	0	9	3	0
26	10	0	12	31	0
8	21	0	10	20	0
16	24	0	27	17	0
31	24	0	12	11	0
14	31	0	31	2	0
3	18	0	27	16	0
4	14	0	10	3	0
17	27	0	16	25	0
-99	-99	0	-99	-99	0





RANDPTS3			RANDPTS4		
X	Y	JT	X	Y	JT
1	18	0	20	30	0
24	13	0	12	3	0
20	30	0	8	4	0
12	3	0	25	3	0
8	4	0	16	23	0
25	3	0	24	3	0
16	23	0	14	18	0
24	3	0	22	10	0
14	18	0	22	7	0
22	10	0	12	16	0
22	7	0	10	20	0
12	16	0	7	28	0
10	20	0	30	6	0
7	28	0	1	2	0
30	6	0	20	32	0
1	2	0	5	13	0
20	32	0	1	14	0
5	13	0	5	15	0
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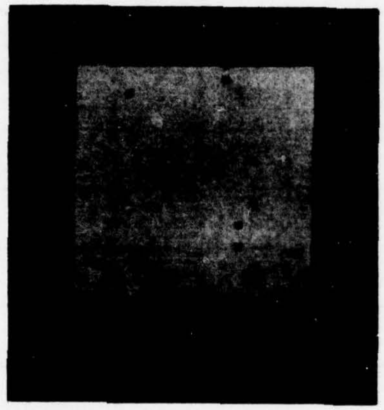
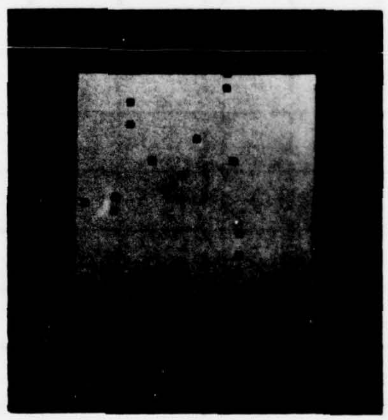
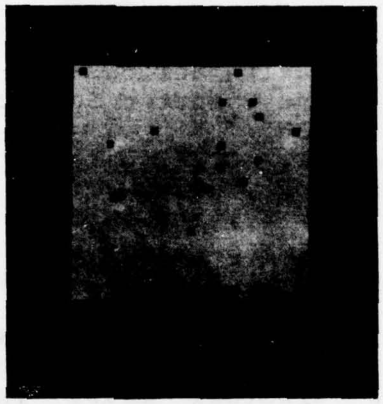
-99	-99	0	-99	-99	0





RANDPTS5					
X	Y	JT			
11	23	0			
20	27	0			
5	21	0			
20	18	0			
16	9	0			
25	25	0			
24	27	0			
22	31	0			
22	1	0			
12	1	0			
22	1	0			
17	18	0			
20	21	0			
6	14	0			
25	1	0			
31	5	0			
1	31	0			
30	23	0			
25	19	0			
23	16	0			
-99	-99	0			



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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Image processing
Pattern recognition
Correlation
Registration
Matching
Point patterns

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report investigates the problem of matching two different sketches of the same scene. The process of matching enables pairing of corresponding parts of the two sketches thus allowing registration of one sketch with respect to the other. Once registered, detection of matching subpatterns and/or discrepancies is possible.

Sketches are represented as structured arrays of points...

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20. Abstract (continued)

(Cartesian coordinates and other associated information which embody the most important features of the sketch).

Two sketches are matched by comparing all point pairs of one sketch with those of the other. The decision as to whether or not one point pair (fuzzily) matches another is based on how well the length and slope of the imaginary line segment between the first pair coincides with the length and slope of the second pair.

The power of the matching process is tested by adding varying amounts of noise--in the form of Brownian motion, rotation, rescaling, random point additions/deletions--to determine how fast successful performance degrades.

Several means of reducing/combatting the effects of noise are considered. The two most important ideas are adding additional information about each point and attempting to determine the rotation/scaling of one sketch with respect to the other. Suggestions for further research are also included.